

NITROGEN DYNAMICS IN A PECAN (*Carya illinoensis* K. Koch)-COTTON
(*Gossypium hirsutum* L.) ALLEY CROPPING SYSTEM IN THE SOUTHERN UNITED
STATES

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2003

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by

Samuel Clifton Allen

This work is dedicated to the memory of my mother, Harriet Elise Priester Allen
(15 December 1933 – 24 October 2002).

ACKNOWLEDGMENTS

This project represents a team effort on the part of many people at both the Milton and Gainesville campuses of the University of Florida. I must first express my sincerest thanks to my graduate committee chair Dr. Shibu Jose (UF Milton), whose ongoing direction, encouragement, and financial support via a graduate assistantship made this study a reality. Dr. P.K. Ramachandran Nair (UF Gainesville), my committee cochair, was a great source of inspiration during this study of agroforestry as well. I am also grateful to my committee members Drs. Barry Brecke, Tim Martin and Peter Nkedi-Kizza for their contributions to this study and for their ongoing support of my academic progress.

I am deeply grateful for the gracious and professional assistance provided by the faculty and staff of the West Florida Research and Education Center (WFREC) of the University of Florida (Milton) during the entire course of this study. Specifically, I wish to thank Dr. Jeffrey Mullahey (Center Director), Chris Gilmore, Lisa Griswold, Amanda Larsen, Barbara May, Nik McCue, Sara Merritt, Rick Puckett, Josiah Raymer, Jeanette Ross and Robin Vickers, and others at WFREC who have contributed to the successful implementation of this study. I would also like to extend my special thanks to Dr. Leonard Dunavin, Associate Professor Emeritus, who was never too busy to provide a listening ear. Very special thanks are due to Drs. Kyehan Lee and Craig Ramsey, two outstanding postdoctoral researchers who have been my patient friends and mentors over the past two years. Many fellow graduate students at UF Milton have provided me with

practical help or moral support as well, and these include my friends Maheteme Gebremedhin, Dawn Henderson, Sanjaya Ranasinghe, Andrew Ruth, Robert Wanvestraut and Diomides (Diomy) Zamora. Thanks are also due to the many OPS and student workers at UF Milton who have helped with data collection, sample preparation, logistical support or other assistance—Chris Adkison, Sean Claypool, Brenda Hahr, Cathy Hardin, Clay Hayes, Mitch Johnson, Jason Liddle, Jennifer Liddle, Leah McCue, Chris Payne, Troy Rutherford, David Vaughn, Lewayne White and Andy Whitehurst. Lastly, I must thank Doug Hatfield (farm manager), Tim Baxley, Sydney Betz, Michael Dozier, Greg Kimmons, Rex Lawson, Kenny McCreless, Robert Murrell, Joe Nelson, Thomas Salter III, Vernon Tedder and the other staff of the WFREC Farm (Jay, Florida), who provided the expert field support that made this study possible.

My appreciation is also expressed to the many people within the School of Forest Resources and Conservation (SFRC) and the larger Gainesville campus of the University of Florida, who provided assistance, advice or encouragement during this study. This includes Dr. Wayne Smith (SFRC Director) and the many faculty under whom I have had the pleasure of studying since August 1999, including Drs. Henry Gholz, Eric Jokela, Timothy Martin, P.K. Nair, Donald Rockwood, Robert Schmidt and Timothy White. I appreciate the key involvement of Drs. Michael Bannister and Sarah Workman of the Center for Subtropical Agroforestry (CSTAF) as well. Lastly, I want to acknowledge the assistance of the very capable staff of the SFRC, which includes Cherie Arias, Dawnette Lauramore, Cindy Love, Marie Meldrum, Scott Sager, Sherry Tucker, Willie Wood and others.

Thanks are expressed to Drs. Hector Adegbidi, Vimala Nair and Don Graetz (Soil and Water Science) for their key involvement in the latter phases of the study, and to Dr. Ken Woodard (Agronomy) for his expert guidance on lysimeter construction and operation. Thanks are also due to Elizabeth Kennelly, Beverly Welch, and the staff of the UF Analytical Research Laboratory (ARL) for carrying out the soil and water analyses, and to Dr. Jason Curtis (Geological Sciences) for conducting the stable isotope analysis.

I wish to give credit to my mentors in the field of forestry and agroforestry, some of whom have already been cited (Drs. Shibu Jose and P.K. Nair), as well as Drs. Felix Eslava, Rodel Lasco and Enrique (Ike) Tolentino, of the University of the Philippines at Los Baños, and Jeff Palmer and Harold Watson, formerly of the Mindanao Baptist Rural Life Center, Davao del Sur, Philippines. I also wish to thank the many other friends who have inspired and befriended me during my graduate student days, including Andrea Albertin, Michelle Andrianarisata, Dr. Kent Apostol, Dr. Chip Appel, Kathlene Aroño, Kathryne Aroño, Mario Aviles, Brian Becker, John Bellow, Fred Boltz, Richard Cardellino, Tammie Coffman, Alyson Dagang, Kristen Davis, Dr. Armando and Ruth De la Cruz, Mark Drew, Dr. Edward Ellis, Dr. Rico Gazal, Jennifer Hale, Jimmy Knowles, Dr. Raj and Lena Kumar, Marcus LaPratt, Sichin and Dong Liu, Dr. David May, Robert McGarvey, Dr. Robert Miller, Soumya Mohan, Abiud Mwale, Nicole Mytyk, Dr. J.L. and Lynette Peeples, Dr. Stephen Trolove, Dom and Carleta Underwood, Keith Yearwood and Dr. Yu Xiao. A thank you is also reserved for Daniel and the crew at Jin Jin Chinese restaurant (Milton) for providing numerous hot, nourishing late-evening meals to a hungry graduate student.

Lastly, I wish to express my heartfelt thanks to my wife, Carina (Teri) Allen, for her ongoing moral support and encouragement, and for her gracious help with field work and sample preparation, in which she always managed to be “beautiful while busy.” I am also thankful to Walter Allen and Kelli Sue Allen, my brother and sister-in-law, for their great encouragement and prayers, and to my late parents, Dr. James and Harriet Allen, who always had confidence in me. Most importantly, I give all credit and honor from this study to God, the Author of all Creation, and to Jesus Christ, who designed our world in such a beautiful, intricate way, and who desires that all should come to know Him and to benefit from this earthly inheritance, both now and in future generations.

This study was funded in part by two grants from the USDA Southern Region Sustainable Agriculture Research and Education (SARE) program (# GS01-009 and # LS02-136), and by a grant from USDA-IFAFS (# 00-52103-9702) through the Center for Subtropical Agroforestry of the University of Florida.

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Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

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May 2003

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Major Department: School of Forest Resources and Conservation

A pecan-cotton alley cropping system was established in northwestern Florida in Spring 2001 to assess tree-crop competition for nitrogen (N) and its effect on mineralization rates and groundwater nitrate levels, and nitrogen use efficiency. Polyethylene root barriers were used to prevent belowground interaction between pecan and cotton in half the number of test plots, for the duration of the 17-month study (June 2001-October 2002).

The study first examined the effect of tree roots on nitrogen transformations in soil. It was observed that temporal variations in net ammonification, nitrification and mineralization were driven primarily by environmental factors (such as soil moisture content and soil temperature), and by initial ammonium and nitrate levels. In general, greater nitrification and mineralization rates were observed in the non-barrier treatment due to higher soil nitrogen. Cotton lint yield reductions were observed in the non-barrier

treatment during both years compared to the barrier treatment, likely due to interspecific competition for water. In addition, source of N was found to have a significant effect on cotton yield, with inorganic fertilizer resulting in higher yields in the barrier treatment compared with organic poultry litter.

The study also examined the “safety net” hypothesis to determine whether tree roots were able to capture nitrate and ammonium leached below the crop root zone. In general, the presence of trees in the non-barrier treatment resulted in decreased soil solution nitrate concentrations and nitrate leaching rates.

Lastly, the results indicated that competition for fertilizer N was minimal because of differences in temporal patterns of pecan and cotton nitrogen demand, although NDF may have occurred in unstudied portions of pecan tree tissue. Nitrogen use efficiency of cotton in barrier treatment was shown to be higher, indicating a greater ability to utilize the available nitrogen.

Overall, this study reveals that the competitive presence of trees can be utilized to decrease soil nitrate concentrations and reduce nitrate leaching. This knowledge will help to improve our understanding of temperate alley cropping systems and to design systems that utilize the safety net process to maximize nitrogen use efficiency and minimize groundwater pollution.

CHAPTER 1 INTRODUCTION

Individuals and institutions in the world's temperate regions are increasingly taking notice of the science and art of alley cropping. This is due in part to growing concerns over the long-term sustainability of intensive monocultural systems. In the temperate context, alley cropping involves the planting of timber, fruit or nut trees in single or multiple rows on agricultural lands, with crops or forages cultivated in the alleys (Nair 1993, Garrett and McGraw 2000). Major purposes of this type of agroforestry system include production of tree or wood products along with crops or forage; improvement of crop or forage quality and quantity by enhancement of microclimatic conditions; improved utilization and recycling of soil nutrients for crop or forage use; control of subsurface water levels; and provision of favorable habitats for plant, insect or animal species beneficial to crops or forage (USDA 1996, Garrett and McGraw 2000).

In the southern United States, pines (*Pinus* spp.) have been intercropped with row crops such as cotton (*Gossypium* spp.), peanuts (*Arachis hypogaea*), maize (*Zea mays* L.), soybean (*Glycine max.* L. (Merr.)), wheat (*Triticum* spp.), oats (*Avena* spp.) and watermelon (*Citrullus lanatus*) (Zinkhan and Mercer 1997; Ramsey and Jose 2001). Pecan (*Carya illinoensis* L.), an important nut-bearing species, has been intercropped with soybean, squash (*Cucurbitaceae* spp.), potatoes (*Solanum tuberosum*), peaches (*Prunus persica*), raspberries (*Rubus* spp.), various grains, and other crops (Nair 1993; Williams et al. 1997; Zinkhan and Mercer 1997; Cannon 1999; Long and Nair 1999; Reid 1999; Ramsey and Jose 2001).

As an association of plant communities, alley cropping is deliberately designed to optimize use of spatial, temporal and physical resources by maximizing positive interactions (facilitation) and minimizing negative ones (competition) between trees and crops (Jose et al. 2000a). For example, trees in these systems are capable of improving soil nutrient status and mineralization patterns (Nair 1993, Palm 1995, Rowe et al. 1999), thereby improving overall system productivity. Trees are also capable of capturing and recycling leached fertilizer nutrients and are thus a potential moderating factor in groundwater pollution caused by leaching of nitrate ($\text{NO}_3\text{-N}$) (Williams et al. 1997, Garrett and McGraw 2000). In addition, trees on agricultural lands offer landowners the possibility of accruing carbon via the sequestration of stable carbon stock, an added incentive for adopting alley cropping (Dixon 1995, Williams et al. 1997, Sampson 2001, Nair and Nair 2003). However, adoption of alley cropping and other agroforestry systems has been hampered by a lack of information on how interspecific interactions affect system management, productivity and sustainability. This is especially true for temperate agroforestry systems, where research efforts have gained momentum only in recent years.

The effect of the tree-crop environment on nitrogen (N) ammonification, nitrification and mineralization patterns in understory soil is an important first consideration in the design of alley cropping systems. Because nitrogen is generally the most limiting nutrient in agricultural soils, improving the prediction of nitrogen transformations in soil is important in being able to maximize usage of natural and applied nitrogen by crops, and in improving and maintaining site productivity and water quality (Mary et al. 1999).

This holds true for both organic and inorganic sources of fertilizer N. The use of poultry litter, for example, as an organic fertilizer for cotton production has been studied in recent years (Nyakatawa et al. 2000, Malik and Reddy 2001). Hence, understanding the nutrient release patterns from organic fertilizer compared with conventional inorganic fertilizer is important in managing organic inputs and optimizing productivity in agroforestry systems.

Equally important to agricultural system sustainability is the fate of nitrogen fertilizers and their effect upon groundwater quality. On a national scale, over-application of N increases the production costs of farmers by millions of dollars each year (USDA 1998a). Moreover, because nitrates are highly soluble, they are easily transported through the soil matrix (Aclion et al. 1997), where they may be carried away by runoff, or leached through the soil profile into the water table (USDA 1998a, Nair et al. 1999). Such contamination can create conditions for eutrophication and related ecological disruptions of rivers, lakes, estuaries and aquifers (Johnson and Raun 1995, USDA 1998a, Bonilla et al. 1999, Ng et al. 2000). From a human health standpoint, nitrate is a toxin that can find its way into public water supplies or private drinking water wells. Nitrate-contaminated drinking water has been shown to cause a respiratory deficiency known as methemoglobinemia ("blue baby syndrome") in infants under six months of age, and similar problems in elderly adults (Sawyer et al. 1994, Baker 1998, Bonilla et al. 1999, Ng et al. 2000, Reddy and Lin 2000).

In this regard, the effect of trees in alley cropping systems is of interest due to the mechanism of nutrient capture, in which deep roots of trees serve as a "safety net" for capturing nitrates and other nutrients that leach below the root zone of crops (van

Noordwijk et al. 1996, Rowe et al. 1999). At lower depths, tree roots can exploit subsoil nitrate beyond the rooting depths of crops. A portion of these nutrients that are absorbed by the trees are later returned to the soil surface through decomposition of fine roots and litterfall, representing a gain to the soil nutrient pool (Nair 1993, Jose et al. 2000b). This phenomenon is of importance because it serves as a possible mechanism for nutrient conservation as well as groundwater clean-up.

From an agronomic standpoint, the effects of tree-crop interactions must ultimately be considered in light of plant nutrient use efficiency and productivity. In general, interspecific competition for nitrogen is an important determinant of productivity since N is generally limiting in such systems. Nitrogen is lost via various biogeochemical processes such as volatilization, denitrification and leaching. Nitrogen is also lost when crop biomass is removed from the field following harvest. In addition, plants of the same species and growth stage can compete heavily for soil nitrogen when depletion zones of neighboring plants overlap. Moreover, in alley cropping systems, competitive forces can be even more intense, as most tree species have the bulk of their fine, feeder roots in the top 30 cm soil layer, thus placing them in a zone of competition with crop species for water and nutrients (Rao et al. 1993, Lehmann et al. 1998a). Tree-crop systems must therefore be properly designed and managed in order to maximize fertilizer use efficiency and minimize deleterious effects of competition on crop yield.

The extent of competition between two species will depend on factors such as nutrient and water availability, root architecture, rooting depth and proximity to competing roots, and temporal nutrient demand (Jose et al. 2000a). For example, the peak intensity of nutrient demand in trees and crops may differ by several months. Trees

tend to exhibit highest nutrient demand in spring during leaf formation, while for crops such as cotton, the demand would be highest in mid-summer during boll formation.

Pecan-based alley cropping systems offer potential for landowners in the southern United States, given the large number of pecan orchards in the region, and the possible environmental and financial benefits that may be accrued from such systems. However, the fate of nitrogen in such systems remains a critical, largely unstudied factor affecting system productivity and sustainability. While nitrogen losses cannot be avoided completely, losses can be minimized through appropriate fertilizer and orchard management practices and by knowledge of how nitrogen moves in the soil-tree system (Herrera and Lindemann 2001). Thus, more understanding is needed of the interactive dynamics of nitrogen in tree-crop systems, in order to maximize fertilizer use efficiency and optimize production from each component.

A 17-month research project was conducted at the West Florida Research and Education Center Research Farm of the University of Florida (Jay) to examine the competitive interactions involving nitrogen in a pecan-cotton alley cropping system. It is important to have sound knowledge of the nitrogen dynamics in alley cropping systems so that successful systems can be developed and optimized. This research will aid the efforts of researchers and landowners to make alley cropping an ecologically viable and environmentally appealing land use practice.

This study was therefore undertaken with the following three objectives:

- To determine the effect of tree-crop competition on nitrogen ammonification, nitrification and mineralization patterns;

- To determine the degree to which nutrient uptake in trees affects groundwater ammonium ($\text{NH}_4\text{-N}$) and nitrate ($\text{NO}_3\text{-N}$) levels and leaching rates; and
- To quantify competition for nitrogen between pecan and cotton.

These objectives comprise chapters 2, 3 and 4 of this dissertation, respectively.

Chapter 5 presents a summary and conclusion.

CHAPTER 2
NITROGEN MINERALIZATION UNDER A PECAN (*Carya illinoensis* K. Koch)-
COTTON (*Gossypium hirsutum* L.) ALLEY CROPPING SYSTEM IN THE
SOUTHERN UNITED STATES

Introduction

Nitrogen (N) is generally the most limiting nutrient in agricultural soils. Improving the prediction of N ammonification, nitrification and mineralization patterns in soils is therefore important in being able to maximize usage of natural and applied nitrogen by crops, and in improving and maintaining site productivity and water quality (Mary et al. 1999).

Alley cropping systems modify the status of soil nutrients in various ways. Generally, the inclusion of woody species on farmlands improves soil fertility. For example, trees help to increase the organic matter content of soil through the addition of leaf litter and other parts from trees, and they generally provide for more efficient cycling of nutrients (Nair 1987, Palm 1995). A tree-soil system can also moderate extreme soil reactions via the increased soil organic matter, improve nutrient release and availability patterns, and provide a more suitable environment for beneficial microorganisms in the rooting zone (Nair 1987, Lee and Jose 2003). However, in many instances, tree roots can lower soil nutrient availability of the associated crop species through competition for water and nutrients (Jose et al. 2000a,b). The long-term effects of nutrient depletion by tree roots on soil N mineralization have not been explored in temperate agroforestry systems.

In addition, the use of organic sources of nitrogen has become an important practice in low input production systems such as alley cropping and organic farming. For example, the use of poultry litter as an organic fertilizer for cotton production has been reported in recent years (Nyakatawa et al. 2000, Malik and Reddy 2001). Poultry litter, which is high in nitrogen, is viewed as a viable alternative to conventional fertilizers, provided that it is applied at an appropriate rate and timescale for crop production (Mitchell and Donald 1999). Understanding nutrient release patterns in poultry litter and comparing them with those in conventional inorganic fertilizer is an important first step in managing organic inputs in alley cropping and other agroforestry systems.

Rates of soil N mineralization often vary with the amount and composition of soil organic matter, soil water availability and soil temperature (Reich et al. 1997, Noble and Randall 1998, O'Connell and Rance 1999). The rate of N mineralization can be affected by physical, chemical, biochemical, and microbiological properties of soils (Deng and Tabatabai 2000). Although several studies have examined the factors affecting soil N mineralization in tropical agroforestry systems (e.g., Palm and Sanchez 1991, Ikerra et al. 2001, Menezes et al. 2002), such studies have been few in temperate agroforestry systems (Thevathasan and Gordon 1997, Seiter and Horwath 1999).

The first objective of this study was to examine the effect of belowground root competition by trees on soil nitrogen mineralization. We hypothesized that tree root competition would lower ammonium ($\text{NH}_4\text{-N}$) and nitrate ($\text{NO}_3\text{-N}$) levels in soil in the non-barrier treatment, which would eventually result in lower rates of N mineralization and crop yield. The second objective was to compare mineralization rates between organic poultry litter and regular inorganic fertilizer. Since the alley cropping system

was established in a 49-year-old pecan orchard fallowed for 29 years prior to initiation of this study, the fallow effect on mineralization and cotton yield was also examined.

Materials and Methods

Study Area and Configuration

This study was conducted at the West Florida Research and Education Center Farm of the University of Florida, located near Jay in northwestern Florida, USA (30°89' N Lat., 87°13' W Long.). The climate is temperate with moderate winters and hot, humid summers. The soil at the site is classified as a Red Bay sandy loam, which is a fine-loamy, siliceous, thermic Rhodic Paleudult. The average water table depth is 1.8 m. The main chemical characteristics of the soil are described in Table 2-1.

For the current study, a pecan-cotton alley cropping system was initiated in Spring 2001 from an existing orchard of pecan trees planted in 1954. The orchard, arranged in a 5x20 grid pattern with trees spaced 18.28 m apart, had remained under non-intensive clover (*Trifolium* spp.) and ryegrass (*Lolium* spp.) production for 29 years prior to the initiation of the current study. For the study, ten plots were demarcated within the orchard and arranged into five blocks using a randomized complete block design. Each plot, which consisted of two rows of trees oriented in a north-south direction, was 27.43 m long and 18.28 m wide, with a practical cultivatable width of 16.24 m, and was separated from its adjacent plot by a buffer zone of the same dimensions.

To assess tree root competition, each block was randomly divided into a barrier plot and a non-barrier plot. Barrier plots were subjected to a root pruning treatment in March of 2001 in which a trenching machine was used to dig a 0.2 m wide x 0.9 m deep trench along both sides of the plot at a distance of 1.5 m from the tree line to separate root

systems of pecan and cotton. A double layer of 0.15 mm-thick polyethylene sheeting was used to line the ditch prior to mechanical backfilling. The barrier plots thus served as the tree root exclusion treatment, preventing interaction of tree and cotton roots, while the non-barrier plots, which did not receive this treatment, served as the tree-root competition treatment. A sixth block was added in Spring 2002 to create an additional barrier and non-barrier plot of the same dimensions as the other plots, forming 12 plots total for the alley cropping system. For control purposes, three additional plots in the orchard were maintained as a pecan monoculture (no cotton plants), and two plots in an adjacent field were maintained as a cotton monoculture (no pecan trees).

In addition to the root-barrier study, a second study was initiated in the same alley cropping system in June 2002 to assess differences in mineralization rates between regular inorganic fertilizer and organic poultry litter. For both barrier and non-barrier plots, half (six) of the plots received regular inorganic fertilizer at a rate of $89.6 \text{ kg N ha}^{-1}$, and half (six) received organic poultry litter at an equivalent rate.

Plot Layout and Fertilizer Application

For this study, cotton (DP 458 B/RR) was planted in rows 0.91 m apart at 16 rows per alley in a north-south orientation on 16 May 2001 and 13 May 2002, after disking of the alleys. A 3-9-18 fertilizer blend was applied to test plots at a rate of $89.6 \text{ kg N ha}^{-1}$ on 19 June 2001 and 5 June 2002. For the 2002 application, half of the test plots received the conventional inorganic fertilizer, and half received organic poultry litter (2-3-2 analysis) (Black Gold Compost Co., Oxford, Florida) that was distributed using a rotary manure spreader. Application of poultry litter was in split applications, with 2/3 rate

being distributed on 5 June, and 1/3 rate being distributed on 24 June. Conventional insecticide and herbicide were applied during the growing season as recommended.

Sampling Methods

Monthly ammonification, nitrification, and N mineralization were determined from July 2001 to October 2002 using the in-situ buried bag technique (Eno 1960) at specific distances (0, 1.5, 4.2 and 8.4 m from tree) in tree rows and alleys (Figure 2-1). For each of 10 (later 12) plots, soil was collected from 7 sites per plot: at tree base, on the first, fourth and eighth rows of cotton, and at commensurate distances in the tree row. For each sampling site, soil samples were collected in pairs in the top 10 cm of soil using a hand spade, after which half were removed to the lab for processing and half were placed into 0.05 mm-thick Fisherbrand polyethylene zipper-seal bags (12.7 cm x 20.32 cm) and returned to the soil profile for month-long incubation. Coarse roots and large organic debris were removed by hand to avoid extraneous N immobilization during incubation. Following incubation, the in-situ samples were collected and transported to the laboratory for processing. All soil samples were kept at 4°C until processing.

From each soil sample, a 20 g subsample was separated for ammonium and nitrate extraction, and an 18-22 g subsample was collected for water content determination. Soil water content was determined gravimetrically by drying a subsample for 24 hours at 105°C. For N extraction, 20 g of soil was mixed with 50 ml of 1 M KCl solution in a 120 ml sample vial, shaken for 1 hr using a Lab-Line Orbit Shaker (Barnstead International, Dubuque, Iowa), allowed to equilibrate for 24 h, and 20 ml of extractant was gravity filtered and then frozen in 20 ml scintillation vials (Keeney and Nelson 1982).

The samples were analyzed for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ content by the Analytical Research Laboratory of the University of Florida (Gainesville, Florida) using an Alpkem Flow Solution IV semi-automated spectrophotometer according to EPA methods 350.1 (for $\text{NH}_4\text{-N}$) and 353.2 (for $\text{NO}_3\text{-N}$). Values were expressed in mg kg^{-1} of dry soil.

Assuming no N losses to plant uptake, leaching or volatilization, monthly net ammonification, nitrification and mineralization rates were calculated as follows (Hart et al. 1994, Reynolds et al. 2000):

$$\text{Net ammonification} = ((\text{NH}_4^+\text{-N})_{t+1} - (\text{NH}_4^+\text{-N})_t); \quad (2-1)$$

$$\text{Net nitrification} = ((\text{NO}_3^-\text{-N})_{t+1} - (\text{NO}_3^-\text{-N})_t); \quad (2-2)$$

$$\text{Net mineralization} = ((\text{NH}_4^+\text{-N} + \text{NO}_3^-\text{-N})_{t+1} - (\text{NH}_4^+\text{-N} + \text{NO}_3^-\text{-N})_t); \quad (2-3)$$

where

t = initial time of sampling, and

t+1 = final time of sampling.

In addition, cotton was harvested at the end of each growing season to determine lint yield per row. For both years, two 6.1 m sections were hand harvested from each row, and lint yield was reported in kg ha^{-1} . Yield of nearby control plots (cotton monoculture) was also determined by hand harvest. Monthly precipitation, air temperatures and soil temperatures (at 10 cm depth) for the study period were calculated from weather data kept on record at the Jay, Florida research station.

Data Analyses

Statistical analyses were performed using SAS 8.2 for Windows (SAS Institute, Cary, North Carolina) using ANOVA within the framework of a split block design. The Shapiro-Wilk's test, in combination with ocular inspection of histogram plots, was used

to test all data for normal distribution. Logarithmic [$\log(x + 1)$] transformation was conducted when such transformation improved normality, and as a result, cotton yield data were transformed prior to analysis. Differences between means were determined using the Least Squares Means procedure. Treatment effects were considered significant at $\alpha = 0.10$.

Results

Soil Water Content

Gravimetric soil water content in the alley and tree row locations was similar throughout the study period (Figure 2-2). The greatest decline in soil water content was observed for September-October 2001, during which soil water content decreased from 17.34% to 2.94% in the alley location, and 17.27% to 3.69% in the tree row location. Soil water content for 2002 was highest in June (12.74% and 9.96% for alley and tree row locations, respectively) and lowest in September (6.78% and 5.46% for alley and tree locations, respectively) of that year.

With regard to treatment, barrier and non-barrier treatments were statistically similar ($p=0.6435$) in soil water content; however, a seasonal effect was observed for both treatments ($p=0.0293$) (Figure 2-2). The non-barrier treatment in particular exhibited a strong seasonal change in water content from growing season one to the dormant season ($p=0.0135$), and from the dormant season to growing season two ($p=0.0160$). The water content of barrier treatment tended to be higher in warm summer months. While not significant for water content, the effect of the barrier treatment was more pronounced for nitrogen mineralization and cotton yield parameters (discussed below).

Initial Soil Ammonium and Nitrate

Initial soil ammonium varied by growing season ($p=0.0045$) but not by treatment ($p=0.2393$) (Figure 2-3). Values for initial soil ammonium generally declined during the study period. Initial soil nitrate exhibited a peak in July 2001 antecedent to fertilizer application, and showed a similar trend in summer 2002. Nitrate levels differed among growing seasons ($p<0.0001$) but not between treatments ($p=0.7655$).

Ammonification

Monthly rates of ammonification did not differ among treatments ($p=0.7776$) or between the alley and tree row locations from July 2001 to September 2002 (Figure 2-4). Overall, net ammonification was observed mostly during the latter part of the first growing season (October through December) for both locations and for the barrier and non-barrier treatments. Net immobilization of $\text{NH}_4\text{-N}$ appears to have occurred during most of the active growing season and during the winter and spring months. For example, the average monthly immobilization for the first growing season (July-November 2001) was 0.10 mg kg^{-1} , and the cumulative immobilization for this same period was 0.41 mg kg^{-1} in the barrier and 0.89 mg kg^{-1} in the non-barrier treatment, respectively. Cumulative seasonal rates are presented in Table 2-2. Cumulative immobilization of $\text{NH}_4\text{-N}$ exhibited no differences among the non-barrier and barrier treatments and for the seasons.

Regression analysis indicated that ammonification was positively correlated with time ($r^2=0.5110$), and negatively correlated with initial water content of soil ($r^2=0.2661$). No significant relationship existed between ammonification and initial ammonium concentration ($r^2=0.1234$) in the soil.

Nitrification

Seasonal differences in nitrification were significant ($p=0.0019$). Lower rates were observed during October through February when average temperature was the lowest (Figure 2-4). Average monthly nitrification rate was 23.1 mg kg^{-1} for the first growing season compared with 19.84 mg kg^{-1} for the second growing season, with no differences among them (Table 2-2). Nitrification exhibited a significant difference between the barrier treatments during growing season one, with non-barrier treatment having a 32% higher cumulative rate than barrier treatment ($p=0.1007$). Nitrification rates exhibited significant ($p=0.0002$) reduction during the dormant season for non-barrier treatment compared with barrier treatment. However, no difference among treatments was observed during the second growing season. Further, nitrification rates did not differ between alley and tree row locations.

Nitrification was weakly but significantly correlated with initial water content ($r^2=0.3478$) and initial nitrate concentration ($r^2=0.1635$). However, nitrification was negatively correlated with time ($r^2=0.2689$).

Mineralization

Temporal variation in mineralization followed a pattern similar to that of nitrification, with lower rates during October through February for both the alley and tree row locations (Figure 2-4). Average monthly mineralization during growing season one was 19.78 mg kg^{-1} for barrier treatment and 26.05 mg kg^{-1} for non-barrier treatment, with a significant difference ($p=0.0750$) between them (Table 2-2). No difference in mineralization was observed for growing season two. However, the non-barrier treatment had 20% lower ($p=0.0156$) mineralization rate during the dormant season.

Mineralization rates showed a positive linear relationship with soil temperature and soil water for both the alley and tree row locations (Figures 2-6 and 2-7). The relationship was stronger for soil water than for soil temperature. Mineralization increased substantially with increasing soil water in the barrier treatment ($r^2=0.8144$; $p=0.0004$), the non-barrier treatment ($r^2=0.8215$; $p=0.0003$), and the tree row location ($r^2=0.5951$; $p=0.0090$).

Regression analysis revealed that higher levels of initial soil $\text{NO}_3\text{-N}$ resulted in increased rates of mineralization for the barrier ($p=0.0636$), but not for the non-barrier treatment (Figure 2-5). The relationship was also significant ($p=0.0225$) for the tree row. No such relationship between mineralization and initial $\text{NH}_4\text{-N}$ was observed for any of the locations or treatments.

Fallow Effect and Mineralization

A comparison of N mineralization rates for the months of July, August and September of 2001 and 2002 was carried out to assess carry-over effects of the pre-2001 fallow period on mineralization. For the three-month observation period, mineralization averaged $33.17 \text{ mg kg}^{-1} \text{ month}^{-1}$ in the first year and $13.21 \text{ mg kg}^{-1} \text{ month}^{-1}$ in the second year, representing a significant ($p=0.0001$) decrease. This second-year decrease in mineralization was observed in both the barrier (63% decrease) and non-barrier (57% decrease) treatment areas.

Initial Nitrogen Source and Nitrogen Transformations

The rates of N ammonification, nitrification and mineralization in the barrier and non-barrier treatments did not vary in response to the source of nitrogen (Figure 2-8). Overall, we observed a net ammonification (0.2 mg kg^{-1} ; pooled for the root trenching

treatments) in soils under inorganic N and a net immobilization under poultry litter for the period from June through September. Mean nitrification rates were 71.8 mg kg^{-1} for the inorganic fertilizer and 79.2 mg kg^{-1} for the poultry litter. Mineralization rates were also similar, with 72.3 and 77.8 mg kg^{-1} for the inorganic fertilizer and poultry litter, respectively.

Cotton Lint Yield

Lint yield in 2001 was significantly ($p=0.0034$) higher in the barrier ($712.36 \text{ kg ha}^{-1}$) compared to the non-barrier ($524.03 \text{ kg ha}^{-1}$) treatment, but was similar to the monoculture ($645.56 \text{ kg ha}^{-1}$) (Figure 2-9). For 2002, cotton in barrier averaged $447.88 \text{ kg ha}^{-1}$, while that in the non-barrier treatment averaged only $180.40 \text{ kg ha}^{-1}$, with significant difference ($p<0.0001$) among them. The monoculture yield ($751.26 \text{ kg ha}^{-1}$) was substantially higher than yield from the barrier and non-barrier treatments as well. Significant differences were also observed between years, with yield in barrier being 37.13% lower in the second year, and yield in non-barrier being 65.58% lower in the second year, compared to respective 2001 yields.

Although source of nitrogen had no effect ($p=0.1197$) on lint yield in the non-barrier treatment, yield was significantly affected ($p=0.0111$) in the barrier treatment (Figure 2-10), resulting in an interaction between treatment and source of nitrogen. Lint yield was 39% higher in the inorganic fertilizer plots ($521.22 \text{ kg ha}^{-1}$) compared to the poultry litter plots ($374.53 \text{ kg ha}^{-1}$) for the barrier treatment.

Discussion

During 15 months of sampling, we found significant seasonal variations in the rates of mineralization, nitrification and ammonification. In both alley and tree row

areas, net mineralization, indicative of plant-available N, peaked during the early growing season, and decreased gradually towards the end of the year, although fluxes were not consistent between seasons. For 2001, net mineralization peaked at 42.44 mg kg^{-1} in July in the non-barrier treatment while the peak for barrier (31.90 mg kg^{-1}) occurred two months later. Apparently, non-barrier treatment responded to the N fertilization with an increased rate of N turnover. Following this was a significant drop in mineralization and nitrification rates, perhaps due to lower rainfall and lower soil temperatures, which may have begun to immobilize nitrogen in the soil. For 2002, net mineralization reached 29.37 mg kg^{-1} in May in non-barrier and 25.95 mg kg^{-1} in June in barrier. Mineralization and nitrification rates observed in our study are within the range reported for both agricultural (Deng and Tabatabai 2000) and forest soils (Pérez et al. 1998).

Overall, rates of mineralization, nitrification and ammonification appeared to follow seasonal patterns of temperature and rainfall. In most regions, the highest rates of N mineralization usually occur in spring and summer (March to July) and rapidly decline in fall and winter (Bielek 1998). For Florida, which has a longer growing season, we observed this decline in September or October. The seasonal variations in N mineralization rates were correlated to soil temperature and soil moisture, as reported previously (Foster 1989, Goncalves and Carlyle 1994).

In addition to seasonal patterns in mineralization, we observed higher mineralization during the first growing season (July-September) compared to the second growing season. One possibility is that the 29-year-long fallow period prior to the initiation of this trial, and the addition of fertilizer N, may have heavily stimulated the mineralization process, a process referred to as the “priming effect” (Bielek 1998, Lovell

and Hatch 1998). For example, Bielek (1998) observed that rapid acceleration of mineralization occurred in more fertile soils than less fertile soils. Our study site has a nutrient-rich topsoil due to the long-term deposition of pecan leaf biomass, and thus major additions of inorganic nitrogen to this system could be expected to exhibit a lowering of C:N ratio of soil (Maithani et al. 1998), which in turn, could accelerate soil N transformations. Although we supplied inorganic or organic N again during the second season, the overall C:N ratio may have increased due to build up of organic matter from cotton residue in the system, or to rapid microbial assimilation of N (Priha and Smolander 1999). Data from a companion study support this hypothesis. The C:N ratio increased from 10.5 during the first growing season to 12.3 during the second growing season in the same study plots (Lee and Jose, unpublished data). These authors reported an increase in soil carbon and a decrease in N during the second growing season compared with the first growing season. It appears that soil fertility during the second growing season decreased considerably compared to the first. A similar effect has been reported in studies of tree fallow systems as well (Kwesiga and Coe 1994, Maroko et al. 1998, Ikerra et al. 2001).

Contrary to our expectations, the non-barrier treatment had significantly higher nitrification and mineralization rates than the barrier treatment during the first growing season. We postulated that roots of non-barrier trees were acquiring N from the fertilized alley, resulting in N depletion in the soil. We further hypothesized that this would eventually lead to reduced rate of N mineralization in the non-barrier treatment compared to the barrier treatment. In a related study we have shown that N uptake by cotton in the non-barrier treatment was significantly lower than that in the barrier treatment (Chapter

4). It is possible that lower N demand by cotton plants as a result of competition for water (Wanvestraut et al. 2003) in the non-barrier treatment has resulted in higher $\text{NH}_4\text{-N}$ in the soil, leading to greater nitrification and mineralization.

One factor that may affect N transformations in the system is pecan leaf litter. Kaur et al. (2000) observed that tree mulch build-up can result in higher N availability under agroforestry systems. Decomposition of pecan tree biomass, which would be expected to follow an exponential decay curve, could affect N levels in the system, by supplying varying amounts of nitrogen at varying times during the year, thus altering litter quality and microbial activity on the orchard floor.

Another consideration is the possibility of chemical inhibition of nitrification by allelopathic compounds in leaf biomass (Clein and Schimel 1995). While this is conceivably possible given the long period of pecan leaf and root biomass accumulation prior to establishment of the system, the effect, if any, would be expected to be uniform throughout the system. While researchers have looked at this possibility in black walnut, their results indicated no inhibitory effect of allelochemicals on nitrification and mineralization in the field (Thevathasan et al. 1999).

Although source of nitrogen did not have any effect on net ammonification, nitrification and mineralization in our study, lint yield was affected in the barrier treatment. Cotton plants responded better to inorganic fertilizer than poultry litter when belowground root competition between pecan and cotton was avoided. Others have reported similar results for cotton grown with poultry litter and inorganic fertilizer (Mitchell et al. 1992). Since similar mineralization rates were observed for both the sources (Figure 2-8), it is unclear why plants responded better to inorganic fertilizer than

poultry litter. As poultry litter is an organic product, the timeframe in which plant available N becomes available may differ from inorganic fertilizer. A finer scale of observation might serve to quantify more clearly the differences in N transformations between the inorganic fertilizer and poultry litter.

Lint yield showed significant decrease (37.1% for barrier and 65.6% for non-barrier) in 2002 compared to 2001 (Figure 2-9). This may be partially explained by differences in N mineralization observed during the three months of active vegetative and reproductive growth of cotton. A direct comparison of N mineralization during this period (July through September) for the two growing seasons revealed significantly lower (60%) mineralization during the second year compared to the first year. Competition for water also appears to be a likely factor for yield reductions, since yield of non-barrier cotton plants was depressed during both years (Wanvestraut et al. 2003).

Conclusions

Temporal variations in net ammonification, nitrification and mineralization were driven primarily by environmental factors (e.g., soil moisture content and soil temperature), and by initial ammonium and nitrate levels. However, these and other factors appear to have exerted a combined influence on N transformations over the study period. Competitive interactions for resources such as water and nitrogen resulted in a decreased ability for nitrogen uptake in plants in the non-barrier treatment compared to those in the barrier treatment. This, in turn, may have resulted in a higher build-up of soil N in the non-barrier treatment. Effects of the pre-trial fallow period appear to have diminished by the second growing season.

Table 2-1. Surface soil chemical characteristics of Rhodic Paleudult sandy loam soil of the Jay, FL agroforestry site.

Soil property	Value
Soil pH	6.0
Organic matter (%)	3.1
CEC (cmol kg ⁻¹)	8.0
Nitrogen concentration (%)	0.1
Phosphorous* (mg kg ⁻¹)	46.0
Potassium* (mg kg ⁻¹)	86.0
Calcium* (mg kg ⁻¹)	636.0
Magnesium* (mg kg ⁻¹)	168.0
Sulfur* (mg kg ⁻¹)	16.0

*water soluble form

Table 2-2. Seasonal and cumulative rates of N ammonification, nitrification and mineralization in barrier and non-barrier treatments.

Observation period	Ammonification (mg kg ⁻¹)		Nitrification (mg kg ⁻¹)		Mineralization (mg kg ⁻¹)	
	Barrier	No barrier	Barrier	No barrier	Barrier	No barrier
2001 Growing Season (July–November)	-0.41 a ¹ A ² (1.88) ³	-0.89 aA (1.57)	99.29 aA (6.26)	131.16 aA (9.09)	98.88 aA (5.21)	130.27 bA (7.72)
2001/2002 Dormant Season (December–April)	-2.02 aA (1.03)	-2.87 aA (1.17)	76.07 aA (2.97)	62.10 aB (2.06)	74.04 aA (2.45)	59.23 aB (1.19)
2002 Growing Season (May–September)	-2.09 aA (0.52)	-2.76 aA (0.89)	95.38 aA (3.03)	103.09 aA (3.13)	93.29 aA (2.99)	100.33 aA (2.50)
Whole Study Period (July 2001–September 2002)	-4.52 (0.68)	-6.52 (0.67)	270.74 (2.40)	296.35 (3.39)	266.21 (2.08)	289.83 (2.97)

¹ Within-season values followed by the same lowercase letter are not significantly different at the 0.10 level of probability.

² Across-season values followed by the same uppercase letter are not significantly different at the 0.10 level of probability.

³ Standard errors of the mean are given in parentheses.

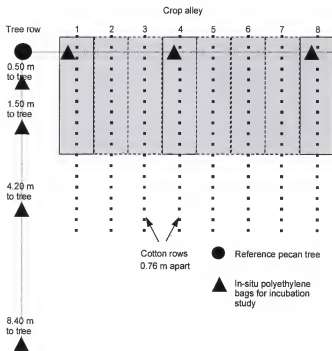


Figure 2-1. Plot layout showing location of in-situ soil incubation bags at the Jay, Florida agroforestry site.

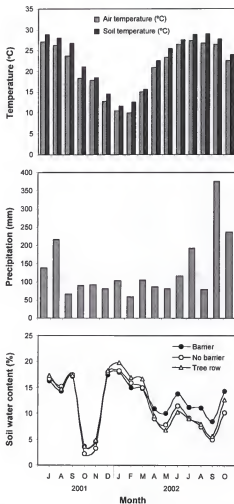


Figure 2-2. Monthly averages for air temperature, soil temperature (at 10 cm depth), precipitation, and soil water content at the Jay, Florida agroforestry site.

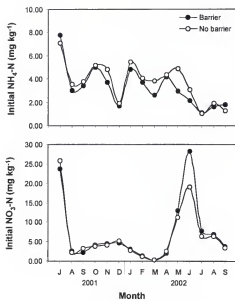


Figure 2-3. Monthly averages of initial soil $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ levels in alleyways of barrier and non-barrier treatments.

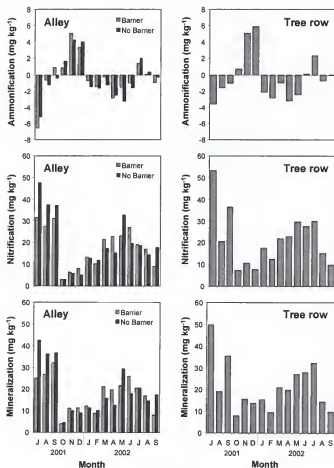


Figure 2-4. Monthly rates of N ammonification, nitrification and mineralization in alley and tree row locations.

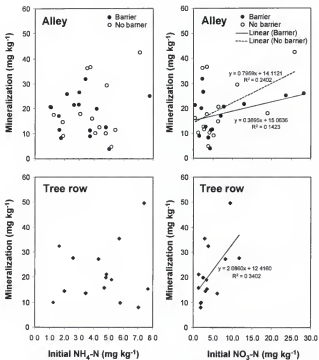


Figure 2-5. Monthly N mineralization rates in alley and tree row locations as influenced by initial levels of NH₄-N and NO₃-N.

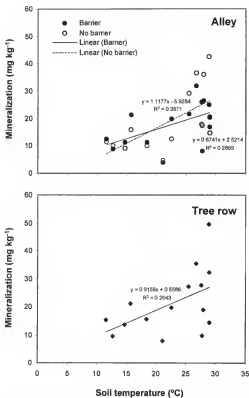


Figure 2-6. Monthly N mineralization rates in alley and tree row locations as influenced by soil temperature (10 cm depth).

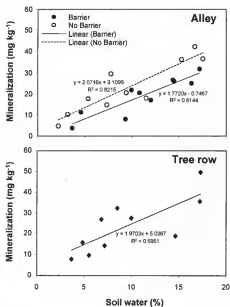


Figure 2-7. Monthly N mineralization rates in alley and tree row locations as influenced by soil water percentage during the 2001 and 2002 growing seasons.

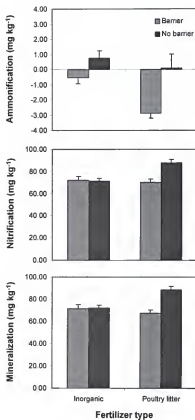


Figure 2-8. Seasonal rates of N ammonification, nitrification and mineralization in alleyways of barrier and non-barrier treatments as influenced by application of inorganic fertilizer vs. poultry litter during the 2002 growing season.

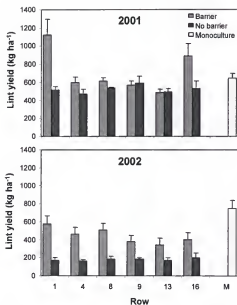


Figure 2-9. Lint cotton yield in barrier, non-barrier and monoculture treatments during the 2001 and 2002 growing seasons.

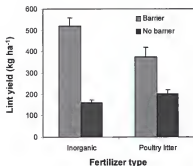


Figure 2-10. Lint cotton yield in barrier and non-barrier treatments as influenced by application of inorganic fertilizer vs. poultry litter during the 2002 growing season.

CHAPTER 3
GROUNDWATER NITRATE DYNAMICS IN A PECAN (*Carya illinoensis* K. Koch)-
COTTON (*Gossypium hirsutum* L.) ALLEY CROPPING SYSTEM IN THE
SOUTHERN UNITED STATES

Introduction

The fate of nitrogen (N) fertilizers and their effect on groundwater quality is of direct importance to farmers, researchers, environmentalists and the general public. Intensive agricultural practices have led to inefficient use of applied nitrogen and to contamination of surface and subsurface drainage water through nitrate leaching (Bonilla et al. 1999, Ng et al. 2000). On a national scale, over-application of N increases the production costs of farmers by millions of dollars each year (USDA 1998a). Moreover, the negative effects of nitrate leaching on rivers, lakes and rural residential wells are of increasing public and scientific concern (USDA 1998b, Bonilla et al. 1999, Ng et al. 2000). Agroforestry has been identified as a land use practice with potential for alleviating some of these problems.

A major form of agroforestry in the USA is alley cropping, which involves the planting of row crops or pasture in alleys formed by single or multiple rows of trees or shrubs (Garrett and Buck 1997). Trees in agroforestry systems are capable of recycling soil nutrients that leach down the crop rooting zone, thereby reducing ground water contamination and increasing nutrient use efficiency in the system (Rowe et al. 1999).

Nitrogen is a limiting soil nutrient in temperate alley cropping systems. It is lost via harvests of crop biomass, litterfall by trees, and by volatilization and leaching processes. In addition, plants of the same species and growth stage compete heavily for

nitrate ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) due to the high mobility of water and nitrate ions along the root surface, resulting in depletion zones in the soil that overlap with neighboring plants. Nitrogen fertilizer supplements are therefore usually needed in order to maintain favorable plant growth.

Similarly, trees and crops possess a high potential for interspecific competition for nitrate in the topsoil, depending on factors such as rooting depth, water availability and tree species phenology (Jose et al. 2000a). Many trees have the bulk of their fine, feeder roots in the top 30-cm deep topsoil, placing them in a zone of competition with crop roots. At lower depths, tree roots can exploit subsoil nitrate and other nutrients beyond the rooting depths of most crops, placing trees at a competitive advantage for acquiring leached nitrogen. In other cases, interspecific competition may not occur if the two species utilize different sets of soil resource horizons or their temporal demands for nitrogen differ. Water availability also affects nutrient competition, directly by decreasing mass flow and indirectly by reducing crop growth rate. Competition, in turn, is mitigated in part by the use of chemical or organic N amendments.

Interspecific competition for nutrients, while present, is generally of minor importance to system productivity in the temperate region. However, certain factors can lead to increased competition for nutrients. For example, Jose et al. (2000b) observed that competition for fertilizer nitrogen was minimal in a black walnut-maize alley crop, since nutrient acquisition was not simultaneous among system components. However, water availability was observed to be a factor in nutrient competition, as competition for water by tree roots was responsible for reduction in biomass in intercropped corn, resulting in decreased efficiency of fertilizer use (Jose et al. 2000b). Similarly, in a

poplar-barley system in southern Ontario, associated trees and crops were found to utilize different sets of soil nutrient resource horizons (Williams et al. 1997). However, competition for available nutrients cannot be avoided when N is limited and fertilizer is not supplied (Chirwa et al. 1994, de Montard et al. 1999, Imo and Timmer 2000).

Intercropped trees can benefit when N is applied to nearby crops, as the nutrient may find its way to nearby tree roots. This form of nutrient capture could be an important factor in the growth of pecan trees, for example, which are often below their potential yielding capacity due to nitrogen deficiency (Arnold and Crocker 1999).

The "safety net" hypothesis of nutrient capture holds that the deep roots of trees are capable of retrieving nitrate and other nutrients that have leached below the rooting zone of associated agronomic crops, and of eventually recycling these nutrients as litterfall and rootfall in the cropping zone. A study in Sweden, for example, focused on the effects of tree harvesting on natural N levels in soil (Browaldh 1996). The study found that natural N levels increased in the vicinity of harvested sites, due to the lack of N uptake by tree roots of harvested trees. In other studies, isotopic tracers such as ^{15}N -enriched fertilizer have been used to trace movement of applied N in alley cropping systems (e.g., Jose et al. 2000b). It is unclear, however, to what extent the safety net role would help in alleviating N leaching in temperate alley cropping systems. Understanding the dynamics of ground water nitrogen with and without tree-crop root interaction would be the first step in making alley cropping an environmentally appealing and ecologically viable land use option for landowners. Hence, the objective of this study was to determine the role of tree roots on groundwater ammonium and nitrate leaching in a pecan-cotton alley cropping system.

Materials and Methods

Study Area and Configuration

This study was conducted at the West Florida Research and Education Center Farm of the University of Florida, located near Jay in northwestern Florida, USA (30°89' N Lat., 87°13' W Long.). The climate is temperate with moderate winters and hot, humid summers. The soil at the site is classified as a Red Bay sandy loam, which is a fine-loamy, siliceous, thermic Rhodic Paleudult. The average water table depth is 1.8 m.

A mature pecan-cotton alley cropping system was established in Spring 2001 from an existing orchard of pecan trees that had been planted at a uniform spacing of 18.28 m in 1954 and that had remained under grass cover for 29 years until the initiation of the current study. For this study, 10 plots were demarcated within the orchard and arranged into 5 blocks using a randomized complete block design (this number was reduced to 6 plots in June 2002 due to the establishment of another study in the orchard (see Chapter 2)). Each plot, which consisted of two rows of trees oriented in a north-south direction, was 27.43 m long and 18.28 m wide, with a practical cultivatable width of 16.24 m, and was separated from its adjacent plot by a buffer zone of the same dimensions.

To assess tree root competition, each block was randomly divided into a barrier plot and a non-barrier plot. Barrier plots were subjected to a root pruning treatment in March of 2001 in which a trenching machine was used to dig a 0.2 m wide x 0.9 m deep trench along both sides of the plot at a distance of 1.5 m from the trees to separate root systems of pecan and cotton. A double layer of 0.15 mm-thick polyethylene sheeting was used to line the ditch prior to mechanical backfilling. The barrier plots thus served as the

tree root exclusion treatment, while the non-barrier plots, which did not receive this treatment, served as the tree-root competition treatment.

Cotton (DP 458 B/RR) was planted in rows 0.91 m apart at 16 rows per alley in a north-south orientation on 16 May 2001 and 13 May 2002, after disking of the alleys. A 3-9-18 fertilizer blend was applied at a rate of 89.6 kg N ha⁻¹ on 19 June 2001 and 5 June 2002. Conventional insecticide and herbicide were applied during the growing season as recommended.

Sampling Methods

Soil solution (free soil water that is not in equilibrium with the soil matrix) (Weston and Attiwill 1996) was sampled 1-2 times monthly over a 15-month period from ceramic cup lysimeters installed in pairs at depths of 0.3 and 0.9 m at specific distances of 1.5, 4.2 and 8.4 m from a reference tree in each plot (Figure 3-1). Lysimeters were fitted with a highly porous (~45% porosity) ceramic cup (Soil Moisture Equipment Corp., Santa Barbara, California) that allowed for collection of soil solution 24-48 hr after application of a vacuum at 30-50 kPa (Talsma et al. 1979). The samples were collected in 20 ml scintillation vials and kept frozen until analysis. Samples were analyzed for NH₄-N and NO₃-N concentrations by the Analytical Research Laboratory of the University of Florida (Gainesville, Florida) using an Alpkem Flow Solution IV semi-automated spectrophotometer according to EPA methods 350.1 (for NH₄-N) and 353.2 (for NO₃-N). Values were expressed in mg L⁻¹.

Data from each month were averaged across rows to produce one composite observation per plot at each depth (van Miegroet et al. 1994). This was necessary because missing data (resulting from dry soil conditions or damaged lysimeters) precluded whole-

study analysis for a row effect. A Hydrosense (Decagon Devices, Pullman, Washington) reflectometry soil moisture probe was used on a monthly basis within a 12 cm surface layer to monitor volumetric water content in all test plots.

Water Drainage

A process-based deterministic model, LEACHMN, the nitrogen component of LEACHM (Leaching Estimation and Chemistry Model; Hutson and Wagenet 1992) was used to calculate subsurface water drainage in the pecan-cotton system. LEACHMN is a simulation model that uses data inputs for weather, crops, and soil profile physical and chemical properties, in determining the movement of water and nitrogen in an agricultural system (Sogbedji et al. 2000, Ng et al. 2001). LEACHMN parameter input values are listed in the Appendix. The model uses the Richard's equation:

$$\partial \theta / \partial t = (\partial / \partial z) [K(\theta)(\partial H / \partial z)] - U(z,t) \quad (3-1)$$

where

θ = volumetric water content ($\text{m}^3 \text{ m}^{-3}$);

t = time (days);

z = depth (mm);

K = hydraulic conductivity (mm day^{-1});

H = hydraulic head (mm); and

U = water lost per unit time by transpiration (day^{-1}).

Leaching of Ammonium and Nitrate

The respective amounts of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ that leached below the root zone at 0.3 and 0.9 m depths in barrier and non-barrier treatments was determined using the following equation (Moreno et al. 1996):

$$L_N = CD \quad (3-2)$$

where

L_N = amount of $\text{NH}_4\text{-N}$ or $\text{NO}_3\text{-N}$ leached (in kg ha^{-1});

C = concentration of $\text{NH}_4\text{-N}$ or $\text{NO}_3\text{-N}$ (in mg L^{-1}) in the sampled soil solution; and

D = respective water drainage (in mm month^{-1}) at the sampled site (as estimated using the LEACHMN model).

Net Retention Index

Net retention index (NRI), a measure of the net effect of tree root uptake on soil $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ levels in a tree-crop system, was derived from the following equation:

$$\text{NRI} = (N_B - N_{NB}) / N_B \quad (3-3)$$

where

NRI = retention of $\text{NH}_4\text{-N}$ or $\text{NO}_3\text{-N}$ (no units);

N_B = amount of $\text{NH}_4\text{-N}$ or $\text{NO}_3\text{-N}$ leached (in kg ha^{-1}) in barrier treatment; and

N_{NB} = amount of $\text{NH}_4\text{-N}$ or $\text{NO}_3\text{-N}$ leached (in kg ha^{-1}) in non-barrier treatment.

For NRI, a value of 0 indicates complete leaching has occurred (i.e., no safety net effect), whereas a value of 1 indicates no leaching has occurred (i.e., complete safety net effect), with values in-between indicating the relative effectiveness of tree roots in intercepting $\text{NH}_4\text{-N}$ or $\text{NO}_3\text{-N}$, all other factors being equal.

Data Analyses

Statistical analyses were performed using SAS 8.2 for Windows (SAS Institute, Cary, North Carolina) using ANOVA within the framework of a split block design. The Shapiro-Wilk's test, in combination with ocular inspection of frequency distributions, was used to test for normality. All data were transformed logarithmically [$\log (x + 1)$]

prior to analysis. Differences between means were determined using the Least Squares Means procedure. Treatment effects were considered significant at $\alpha = 0.10$.

The data set for the 15-month study was analyzed as a whole and in three sub-sets based on season. These seasons, which are referred to in the study as growing season one, dormant season, and growing season two, fell within the following months respectively: June-November 2001, December 2001-April 2002, and May-August 2002.

Results and Discussion

Drainage

Monthly and cumulative field drainage data as estimated using LEACHMN are shown in Figure 3-2. Average monthly drainage at the 0.3 m depth was 48 mm for barrier treatment and 41 mm for non-barrier treatment. Average drainage at the 0.9 m depth was 32 mm and 21 mm, respectively, for the barrier and non-barrier treatments. Values for cumulative drainage, an expression of the sum effect of monthly drainage, were 716 mm for barrier and 614 mm for non-barrier treatments, respectively, at the 0.3 m depth. Cumulative drainage at the 0.9 m depth was 476 mm and 322 mm, respectively, for barrier and non-barrier treatments. A higher drainage in the barrier treatment would be expected given the lack of water uptake by tree roots in that treatment (Jose et al. 2000a, Wanvestraut et al. 2003).

Ammonium Concentrations

In general, concentrations of $\text{NH}_4\text{-N}$ in soil solution were very low and often close to the limit of detection (Table 3-1; Figure 3-3), a result similar to other lysimetric studies (Frazer et al. 1990, van Miegroet et al. 1994). The scarcity of $\text{NH}_4\text{-N}$ in soil solution is not surprising given that NH_4^+ is an exchangeable ion that is easily adsorbed to clay

particles, and that under favorable conditions $\text{NH}_4\text{-N}$ can be quickly oxidized to $\text{NO}_3\text{-N}$ by nitrifying soil bacteria (Breitenbeck and Boquet 1992).

When examined over the duration of the 15-month study period (i.e., eliminating the growing season variable from the analysis), average $\text{NH}_4\text{-N}$ concentrations were not significant for any factor (i.e., treatment, depth, growing season, block) or combination of factors (Table 3-1). Mean concentrations ranged from 0.03 mg L^{-1} in non-barrier (0.3 m depth) to 0.05 mg L^{-1} in non-barrier (0.9 m depth).

Similar results were found when data were analyzed according to season (Table 3-1). Average $\text{NH}_4\text{-N}$ concentrations were significant for changes in growing season ($p=0.0006$) and block ($p=0.0732$) only. Overall $\text{NH}_4\text{-N}$ concentrations for the first growing season (2001) were similar to those in the dormant season, with the exception of the 0.9 m depth in the non-barrier treatment, which increased during the dormant season and remained higher during the second growing season (2002). Average $\text{NH}_4\text{-N}$ concentrations for both depths in the barrier treatment also increased in growing season two compared to levels in previous observation periods.

Nitrate Concentrations

The inorganic N in solution was dominated by $\text{NO}_3\text{-N}$, a result similar to other studies (van Miegroet et al. 1994). Unlike $\text{NH}_4\text{-N}$, the presence of significant amounts of $\text{NO}_3\text{-N}$ in soil solution is expected given that $\text{NO}_3\text{-N}$ is mobile in soils and can be leached from surface to underlying soil layers by percolating rainwater (Breitenbeck 1990). Nitrate concentrations in the soil solution at 0.3 and 0.9 m depths showed strong temporal variations based on season (Table 3-1; Figure 3-3).

When data were analyzed as a whole over the whole study period, $\text{NO}_3\text{-N}$ concentrations were significant for depth ($p=0.0003$) only (Table 3-1). Mean $\text{NO}_3\text{-N}$ concentrations for barrier treatment at 0.3 and 0.9 m depths were 14.36 mg L^{-1} and 10.82 mg L^{-1} , respectively, representing a 24.7% decrease with depth. Mean concentrations for non-barrier at corresponding depths were 10.16 mg L^{-1} and 7.15 mg L^{-1} , respectively, representing a 29.6% decrease.

When examined by season, $\text{NO}_3\text{-N}$ concentration was also significant for depth ($p=0.0025$) (Table 3-1). For growing season one, $\text{NO}_3\text{-N}$ concentration decreased with depth, exhibiting a 54.5% decrease in the barrier treatment and a 44.7% decrease in the non-barrier treatment, respectively. A similar trend for depth was seen in growing season two, where $\text{NO}_3\text{-N}$ concentrations decreased by 35.1% in barrier and 29.6% in non-barrier treatments, respectively. Dormant season trends showed a 91.3% increase with depth in the barrier treatment, but no increase or decrease with depth in the non-barrier treatment.

Seasonal $\text{NO}_3\text{-N}$ concentration was also significant for growing season ($p<0.0001$) and depth x growing season interaction ($p<0.0001$) (Table 3-1). In barrier treatment, the average $\text{NO}_3\text{-N}$ concentrations at 0.3 m depth remained the same for both growing seasons, but were lower in the dormant season. Non-barrier $\text{NO}_3\text{-N}$ concentrations at 0.3 m depth differed for all three seasons, with growing season two being the highest (20.97 mg L^{-1}) and dormant season being the lowest (3.06 mg L^{-1}). For barrier treatment at 0.9 m depth, concentrations for growing season two were higher than those for growing season one. Nitrate concentrations did not differ by season at 0.9 m depth in the non-barrier treatment.

Ammonium Leached

When examined over the whole study period, the average monthly rate of $\text{NH}_4\text{-N}$ leached was not significant for any factor or combination of factors (Table 3-2). This result is expected given the similar findings for overall $\text{NH}_4\text{-N}$ concentrations in the previous section. The average rates of $\text{NH}_4\text{-N}$ leached were in the range of $0.01\text{-}0.02 \text{ kg ha}^{-1} \text{ month}^{-1}$.

On a seasonal basis, statistical analysis showed that the average $\text{NH}_4\text{-N}$ leaching rate was also not significant for any factor or combination of factors (Table 3-2). A comparison of treatment means at the 0.9 m depth in growing season one indicated that the average $\text{NH}_4\text{-N}$ leaching rate for barrier treatment was significantly ($p=0.0794$) higher than that for non-barrier. However, this treatment difference ($0.03 \text{ kg ha}^{-1} \text{ month}^{-1}$) is on too minute a scale for drawing strong conclusions as to significance.

Seasonal and cumulative totals of $\text{NH}_4\text{-N}$ leached are shown in Table 3-3. Analysis of the whole study period showed that total $\text{NH}_4\text{-N}$ leached was not significant for any factor or combination of factors. The total $\text{NH}_4\text{-N}$ leached for the whole study period averaged 0.23 kg ha^{-1} in barrier and 0.14 kg ha^{-1} in non-barrier treatments, respectively, which did not represent a significant difference.

Examined by season, total $\text{NH}_4\text{-N}$ leached was significant for growing season ($p=0.0032$), and there was a treatment x growing season interaction ($p=0.0390$) (Table 3-3). A comparison of treatment means at the 0.9 m depth in growing season one indicated that total $\text{NH}_4\text{-N}$ leached in the barrier treatment was significantly ($p=0.0197$) higher than that in the non-barrier. In addition, total $\text{NH}_4\text{-N}$ leaching levels in the barrier treatment decreased significantly in both depths after the first growing season.

Nitrate Leached

Over the entire 15-month study period, the average rate of $\text{NO}_3\text{-N}$ leaching was significant for treatment ($p=0.0470$) and for depth ($p<0.0002$) (Table 3-2). A comparison of treatment means at 0.9 m depth showed that the barrier treatment mean ($3.40 \text{ kg ha}^{-1} \text{ month}^{-1}$) was significantly ($p=0.0345$) higher than the non-barrier mean ($1.28 \text{ kg ha}^{-1} \text{ month}^{-1}$). With regard to depth effects, for barrier treatment, the mean rate of $\text{NO}_3\text{-N}$ leaching at 0.3 m depth ($9.24 \text{ kg ha}^{-1} \text{ month}^{-1}$) was significantly ($p=0.0237$) higher than the rate at 0.9 m. Similarly, for non-barrier treatment, the rate at 0.3 m depth ($5.50 \text{ kg ha}^{-1} \text{ month}^{-1}$) was significantly ($p=0.0022$) higher than the rate at the deeper depth.

Examination by season showed that the average monthly rate of $\text{NO}_3\text{-N}$ leached was significant for treatment ($p=0.0494$), depth ($p<0.0001$), growing season ($p<0.0001$), and depth x growing season ($p<0.0001$) (Table 3-2). With regard to specific treatment effects, in growing season one, the average $\text{NO}_3\text{-N}$ leaching rate ($3.67 \text{ kg ha}^{-1} \text{ month}^{-1}$) at 0.9 m in barrier treatment was significantly higher ($p=0.0550$) than the rate ($1.27 \text{ kg ha}^{-1} \text{ month}^{-1}$) observed at the same depth in the non-barrier treatment. For the dormant season, a treatment effect was observed for 0.9 m depth, where the average $\text{NO}_3\text{-N}$ leaching rate in barrier ($3.95 \text{ kg ha}^{-1} \text{ month}^{-1}$) was higher ($p=0.0722$) than that for non-barrier ($1.55 \text{ kg ha}^{-1} \text{ month}^{-1}$). A treatment effect for root barrier was not observed in growing season two.

Average $\text{NO}_3\text{-N}$ leaching was also significant for depth, as stated earlier. Growing seasons one and two exhibited a depth effect for both treatments, with lower rates of $\text{NO}_3\text{-N}$ leaching occurring at the lower depth. The dormant season did not exhibit a depth effect within each treatment.

Across seasons, average $\text{NO}_3\text{-N}$ leaching fluctuated in barrier treatment at 0.3 m depth, with the greatest reduction in $\text{NO}_3\text{-N}$ leaching occurring during the dormant season. A reduction in $\text{NO}_3\text{-N}$ leaching during the dormant season also occurred in the non-barrier treatment at 0.3 m. For both treatments at 0.9 m depth, $\text{NO}_3\text{-N}$ leaching rates did not vary significantly when the two growing seasons were compared.

Seasonal and cumulative totals of $\text{NO}_3\text{-N}$ leached are shown in Table 3-3. When examined over the whole study period, total $\text{NO}_3\text{-N}$ leached was significant for treatment ($p=0.0049$) and depth ($p=0.0010$). Specifically, the cumulative amount of $\text{NO}_3\text{-N}$ leached during the entire study period at 0.3 m depth in the barrier treatment ($121.94 \text{ kg ha}^{-1}$) was higher than that leached in the non-barrier treatment (63.83 kg ha^{-1}), representing a decrease of 47.7%. A similar trend occurred at 0.9 m depth, where cumulative $\text{NO}_3\text{-N}$ leaching in barrier (45.56 kg ha^{-1}) was higher than in non-barrier (13.05 kg ha^{-1}), a 71.4% decrease. Cumulative $\text{NO}_3\text{-N}$ leaching rates were also lower at 0.9 m depths compared to 0.3 m depths, in both treatments.

Analysis of total $\text{NO}_3\text{-N}$ leached by season showed overall significant differences for treatment ($p=0.0051$), depth ($p<.0001$), growing season ($p<.0001$), and depth x growing season (0.0006) (Table 3-3). For each growing season, the cumulative amount of $\text{NO}_3\text{-N}$ leached at 0.9 m depth of barrier was greater than three times that for non-barrier, indicating a significant amount of $\text{NO}_3\text{-N}$ being taken up in the non-barrier treatment at the lower depth. Treatments also varied by depth during both growing seasons, with lower depth having a reduced $\text{NO}_3\text{-N}$ leaching rate compared to the upper depth. No significant interactions were observed within the dormant season for either treatment or depth variables.

Various studies have attempted to estimate nitrate leaching rates from agricultural systems. Moreno et al. (1996) conducted a study of water balance and nitrate leaching in an irrigated maize crop on a sandy loam in Spain. They found that nitrate leaching during the 3-year study period totaled 43 kg ha^{-1} under a low fertilization regime ($170 \text{ kg N ha}^{-1} \text{ year}^{-1}$) and 150 kg ha^{-1} under a high fertilization regime ($500 \text{ kg N ha}^{-1} \text{ year}^{-1}$). They observed that main periods of leaching occurred during periods of bare soil and high rain. In another study, Van Miegroet et al. (1994) estimated that 20–40% of the added fertilizer N leached below 60 cm soil depth in a short-rotation sycamore plantation fertilized with 450 kg ha^{-1} of urea over a 3-year period. The results of our study indicated that the barrier treatment had the potential to leach $43.87 \text{ kg N ha}^{-1} \text{ year}^{-1}$ down below 0.9 m depth. The non-barrier treatment, on the other hand, had a potential of leaching only $15.76 \text{ kg N ha}^{-1} \text{ year}^{-1}$ below 0.9 m. For both treatments $\text{NO}_3\text{-N}$ accounted for 99.9% of total inorganic nitrogen.

Net Retention Index of Ammonium and Nitrate

Net retention index (NRI) for $\text{NH}_4\text{-N}$ at 0.3 m depth was similar for both growing seasons and for the whole study period (Table 3-4). NRI for $\text{NH}_4\text{-N}$ was highest at 0.9 m depth during growing season one. The NRI for $\text{NO}_3\text{-N}$ was higher at 0.9 m depths, with mid-range values occurring during growing season one and during the whole study period. The high NRI (0.81) for $\text{NO}_3\text{-N}$ at 0.9 m depth during growing season two is indicative of a significant retention of $\text{NO}_3\text{-N}$ in the non-barrier treatment compared to the barrier treatment during that season. These findings suggest the occurrence of a safety net process on the part of pecan tree roots, particularly at 0.9 m depth.

Similar results demonstrating the safety net role of trees have been reported in the literature. Browaldh (1995), for example, studied the influence of trees on N dynamics in a poplar (*Populus* sp.)-based alley cropping system with oats and barley in Sweden. He found that the presence of trees resulted in lower $\text{NO}_3\text{-N}$ concentrations near the tree, and concluded that the trees were reducing the potential for nitrate leaching. In another study, Lehmann et al. (1998b) found that N leaching losses were 53% lower in an *Acacia saligna*-*Sorghum bicolor* alley cropping system compared to sorghum monoculture. They postulated that reduced leaching could have been due to a higher root abundance and a higher nutrient uptake-to-leaching ratio in the alley cropping system, resulting in higher nutrient use efficiency. Higher rooting density for the non-barrier treatment compared to the barrier treatment has also been reported from our alley cropping system (Wanvestraut et al. 2003). It is possible that the higher rooting density, specifically at deeper horizons, increased nutrient uptake-to-leaching ratio in our non-barrier treatment in comparison to the barrier treatment.

Jama et al. (1998) hypothesized that trees can rapidly root into subsoil and capture $\text{NO}_3\text{-N}$ that has accumulated in agricultural subsoils. They compared inorganic $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in soil to a depth of 3.95 m in 11-month-old stands of calliandra (*Calliandra calothyrsus* Meissner), sesbania [*Sesbania sesban* (L.) Merr.] and other woody perennial species. They found that Calliandra and sesbania reduced soil $\text{NO}_3\text{-N}$ in the top 2 m by 150-200 kg N ha⁻¹.

In a recent study by Rowe et al. (1999), the safety net hypothesis was tested by applying ¹⁵N-labeled ammonium sulfate at three depths in the soil between mixed hedgerows of deep-rooted *Peltophorum dasyrrhachis* and shallower-rooted *Gliricidia*

septum. They estimated that *Peltophorion* took up 42 kg N ha^{-1} and *Gliricidia* took up 21 kg N ha^{-1} from beneath the main crop rooting zone. Their results indicated that the deeper-rooted species had the capacity to act as a safety net, since it was taking up a significant proportion of its N from deeper layers. Although pecan and cotton roots share the top 0.3 m soil layer in our non-barrier treatment, the majority of the roots below 0.6 m have been identified as pecan roots (Wanvestraut et al. 2003). This could be the reason for the high NRI (0.86 for $\text{NH}_4\text{-N}$ and 0.81 for $\text{NO}_3\text{-N}$) observed at 0.9 m in our system.

Conclusions

Overall, the results of our study indicate that the competitive presence of trees can be utilized to decrease soil nitrate concentrations and reduce N leaching in alley cropping systems. The barrier treatment had the potential to leach $43.87 \text{ kg N ha}^{-1} \text{ year}^{-1}$ down below 0.9 m depth. The non-barrier treatment exhibited a significantly lower potential for leaching with only $15.76 \text{ kg N ha}^{-1} \text{ year}^{-1}$ below 0.9 m. For both treatments $\text{NO}_3\text{-N}$ accounted for 99.9% of the total inorganic nitrogen. Further, tree water uptake, in addition to cotton water uptake in the non-barrier treatment, may have decreased water drainage in comparison to the barrier treatment, thereby influencing leaching rates. Overall, the presence of tree roots were observed to be an important factor influencing the fate of nitrogen in the system. These findings will improve our understanding of nitrogen dynamics in temperate alley cropping systems, which in turn, will help in designing systems that can utilize the safety net phenomenon to maximize fertilizer use efficiency while minimizing nitrate contamination of groundwater.

Table 3-1. Seasonal and overall averages of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in soil water extracted from 0.3 and 0.9 m depths in barrier and non-barrier treatments.

Observation period	Average $\text{NH}_4\text{-N}$ concentration (mg L^{-1})			Average $\text{NO}_3\text{-N}$ concentration (mg L^{-1})		
	Barrier		No barrier	Barrier		No barrier
	0.3 m	0.9 m	0.3 m	0.3 m	0.9 m	0.3 m
2001 Growing Season (June–November)	0.04 a ¹ A ² (0.01) ³	0.03 aA (0.02)	0.03 aA (0.01)	18.21 aA (2.96)	8.29 bcA (1.08)	12.82 abA (2.16)
2001/2002 Dormant Season (December–April)	0.02 aA (0.00)	0.02 abA (0.01)	0.02 aA (0.00)	5.86 aB (1.15)	11.21 bAB (1.80)	3.06 aB (0.82)
2002 Growing Season (May–August)	0.11 aB (0.04)	0.09 aB (0.03)	0.06 aA (0.03)	22.10 aA (5.72)	14.34 bcB (1.99)	20.97 abC (5.64)
Whole Study Period (June 2001–August 2002)	0.04 a (0.01)	0.04 ab (0.01)	0.03 ab (0.01)	14.36 a (1.93)	10.82 bc (0.95)	10.16 ab (1.63)

¹ Within-season values followed by the same lowercase letter are not significantly different at the 0.10 level of probability.

² Across-season values followed by the same uppercase letter are not significantly different at the 0.10 level of probability.

³ Standard errors of the mean are given in parentheses.

Table 3-2. Average monthly rates of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ leached at 0.3 and 0.9 m depths in barrier and non-barrier treatments.

Observation period	Average rate of $\text{NH}_4\text{-N}$ leached ($\text{kg ha}^{-1} \text{ month}^{-1}$)			Average rate of $\text{NO}_3\text{-N}$ leached ($\text{kg ha}^{-1} \text{ month}^{-1}$)		
	Barrier		No barrier	Barrier		No barrier
	0.3 m	0.9 m		0.3 m	0.9 m	
2001 Growing Season (June–November)	0.04 a ¹ A ² (0.02) ³	0.04 aA (0.02)	0.03 abA (0.02)	0.01 bA (0.00)	15.15 aA (3.45)	9.37 aA (2.50)
2001/2002 Dormant Season (December–April)	0.00 aB (0.00)	0.00 aB (0.00)	0.00 aA (0.00)	0.02 aA (0.02)	2.45 abCB (0.58)	1.12 cB (0.35)
2002 Growing Season (May–August)	0.01 aAB (0.00)	0.00 aAB (0.00)	0.01 aA (0.00)	0.00 aA (0.00)	9.96 aC (3.76)	7.73 abA (2.88)
Whole Study Period (June 2001–August 2002)	0.02 a (0.01)	0.02 a (0.01)	0.01 a (0.01)	0.01 a (0.01)	9.24 a (1.76)	5.50 ab (1.20)

¹ Within-season values followed by the same lowercase letter are not significantly different at the 0.10 level of probability.

² Across-season values followed by the same uppercase letter are not significantly different at the 0.10 level of probability.

³ Standard errors of the mean are given in parentheses.

Table 3-3. Seasonal and cumulative totals of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ leached at 0.3 and 0.9 m depths in barrier and non-barrier treatments.

Observation period	Total $\text{NH}_4\text{-N}$ leached (kg ha^{-1})				Total $\text{NO}_3\text{-N}$ leached (kg ha^{-1})			
	Barrier		No barrier		Barrier		No barrier	
	0.3 m	0.9 m	0.3 m	0.9 m	0.3 m	0.9 m	0.3 m	0.9 m
2001 Growing Season (June–November)	0.20 a ¹ A ² (0.07) ³	0.19 aA (0.09)	0.11 abA (0.08)	0.02 bA (0.01)	81.81 aA (14.97)	19.08 bA (2.51)	41.23 abA (11.35)	5.09 cA (3.02)
2001/2002 Dormant Season (December–April)	0.02 aB (0.00)	0.02 aB (0.01)	0.02 aA (0.00)	0.12 aA (0.11)	12.24 abB (2.49)	19.76 aA (5.71)	5.59 bB (2.03)	7.42 abA (2.50)
2002 Growing Season (May–August)	0.03 aB (0.01)	0.01 aB (0.00)	0.01 aA (0.01)	0.00 aA (0.00)	27.90 aB (9.98)	6.72 bB (2.86)	17.02 abB (7.32)	0.55 cB (0.51)
Whole Study Period (June 2001–August 2002)	0.25 a (0.03)	0.21 a (0.04)	0.14 a (0.03)	0.14 a (0.04)	121.94 a (9.74)	45.56 b (2.65)	63.83 b (5.79)	13.05 c (1.44)

¹ Within-season values followed by the same lowercase letter are not significantly different at the 0.10 level of probability.

² Across-season values followed by the same uppercase letter are not significantly different at the 0.10 level of probability.

³ Standard errors of the mean are given in parentheses.

Table 3-4. Net Retention Index of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ at 0.3 and 0.9 m depths over two growing seasons and whole study period.

Observation period	NRI of $\text{NH}_4\text{-N}$		NRI of $\text{NO}_3\text{-N}$	
	0.3 m	0.9 m	0.3 m	0.9 m
2001 Growing Season (June–November)	0.33	0.86	0.38	0.65
2002 Growing Season (May–August)	0.33	0.25	0.22	0.81
Whole Study Period (June 2001–August 2002)	0.35	0.13	0.40	0.62

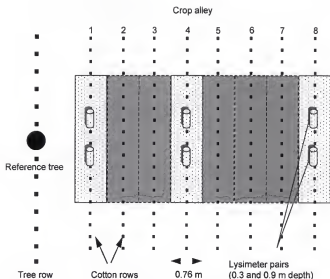


Figure 3-1. Plot layout showing location of suction lysimeters at the Jay, Florida agroforestry site.

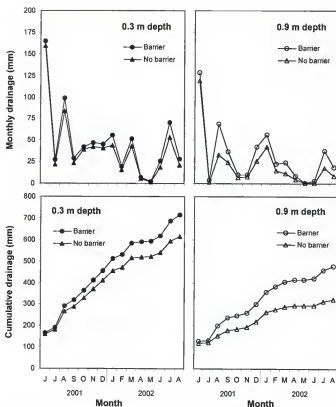


Figure 3-2. Monthly and cumulative drainage values at 0.3 and 0.9 m depths in barrier and non-barrier treatments as estimated using the LEACHMN model.

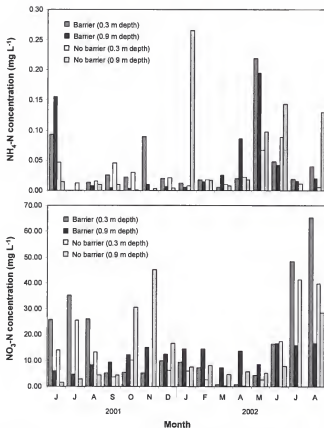


Figure 3-3. Average monthly concentrations of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in soil solution at 0.3 and 0.9 m depths in barrier and non-barrier treatments.

CHAPTER 4

COMPETITION FOR NITROGEN IN A PECAN (*Carya illinoensis* K. Koch)-COTTON (*Gossypium hirsutum* L.) ALLEY CROPPING SYSTEM IN THE SOUTHERN UNITED STATES

Introduction

A primary form of agroforestry in North America is alley cropping, which involves the planting of row crops or pasture in alleys formed by single or multiple rows of trees or shrubs (Garrett and Buck 1997, Gillespie et al. 2000). Important crops for alley cropping in the southern United States include cotton (*Gossypium* spp.), peanut (*Arachis hypogaea*), maize (*Zea mays* L.), soybean (*Glycine max.* L. (Merr.)), wheat (*Triticum* spp.) and oats (*Avena* spp.), combined with trees such as pines (*Pinus* spp.) and pecan. Alley cropping is growing in popularity among landowners who wish to maximize arable land use, diversify production, and increase off-season farm income. The effect of trees in these systems is of interest environmentally as well, in part because trees are capable of capturing and recycling fertilizer nutrients from deeper soil horizons, and thus may help in improving nutrient use efficiency and in mitigating groundwater contamination (Rowe et al. 1999).

Nitrogen (N) is generally the most limiting soil nutrient in temperate alley cropping systems due to various reasons. First, nitrogen is lost via various biogeochemical mechanisms such as volatilization, denitrification and leaching. Nitrogen is also lost when crop biomass is removed from the field following harvest. In addition, plants of the same species and growth stage can compete heavily for nitrogen when zones of depletion in the soil overlap with neighboring plants. Moreover, in alley

cropping systems, competitive forces can be even more intense, as most tree species have the bulk of their fine, feeder roots in the top 30 cm soil layer, thus placing them in a zone of competition with crop species for water and nutrients (Rao et al. 1993, Lehmann et al. 1998a). Thus, tree-crop systems must be properly designed and managed in order to maximize fertilizer use efficiency and minimize deleterious effects of competition on crop yield.

The extent of competition between two species will depend on factors such as nutrient and water availability, root architecture, rooting depth and proximity to competing roots, and temporal nutrient demand (Jose et al. 2000a). Generally, tree roots can exploit subsoil nitrogen and other nutrients beyond the rooting depths of crops, a process that places trees at a competitive advantage for nutrients (Williams et al. 1997). In addition, the peak intensity of nutrient demand in trees and crops may differ by several months, as trees tend to exhibit highest nutrient demand in spring during leaf formation, and crops such as cotton would be at highest demand in mid-summer during boll formation.

In some cases, intercropped trees can receive benefits when fertilizer is applied to nearby crops, as some of the nutrients will be intercepted and taken up by tree roots. This type of secondhand fertilization could be an important factor in the growth of associated tree species in alley cropping systems. Pecan trees, for example, which are often below their potential yielding capacity due to nitrogen deficiency (Arnold and Crocker 1999), could thus benefit from the application of fertilizer to an intercropped row crop.

Pecan-based alley cropping systems offer potential for Southern landowners, given the large number of pecan orchards in the southeastern USA and the possible

environmental and financial benefits that may be accrued from such systems. However, the movement of nitrogen in pecan-cotton systems remains an unstudied but critical factor affecting the growth and productivity of both trees and crops. While nitrogen losses cannot be avoided completely, losses can be minimized through appropriate fertilizer and orchard management practices and by knowledge of how nitrogen moves in the soil-tree system (Herrera and Lindemann 2001). Thus, more understanding is needed of the interactive dynamics of nitrogen in tree-crop systems, in order to maximize fertilizer use efficiency and optimize production from each component.

Hence, the present study was conducted to examine competition for nitrogen between pecan and cotton using ^{15}N -labeled ammonium sulfate fertilizer. Labeled ^{15}N -enriched fertilizer has been used as a nitrogen-tracing technique in cotton (Freney et al. 1993, Rochester et al. 1993, Bondada et al. 1996, Karlen et al. 1996) and to a very limited degree in pecan (Kraimer et al. 2001).

The specific objectives of the study were as follows:

- Quantify the total uptake of nitrogen by trees and cotton with and without interspecific competition;
- Determine if the competition between trees and cotton can change the relative uptake of fertilizer nitrogen;
- Determine whether fertilizer use efficiency of cotton plants is altered as a result of the interspecific competition; and
- Quantify the recovery of fertilizer nitrogen in soil at four successive depths with and without interspecific competition.

Materials and Methods

Study Area and Configuration

This study was conducted at the West Florida Research and Education Center Farm of the University of Florida, located near Jay in northwestern Florida, USA (30°89' N Lat., 87°13' W Long.). The climate is temperate with moderate winters and hot, humid summers. The soil at the site is classified as a Red Bay sandy loam, which is a fine-loamy, siliceous, thermic Rhodic Paleudult. The average water table depth is 1.8 m.

For this study, a pecan-cotton alley cropping system was initiated in Spring 2001 from an existing orchard of pecan trees that had been planted at a uniform spacing of 18.28 m in 1954 and that had remained under grass cover for 29 years until the initiation of the current study. Ten plots were established within the orchard and arranged into five blocks using a randomized complete block design. Each plot, which consisted of two rows of trees oriented in a north-south direction, was 27.43 m long and 18.28 m wide, with a practical cultivatable width of 16.24 m, and was separated from its adjacent plot by a buffer zone of the same dimensions.

To assess tree root competition for nitrogen fertilizer, each block was randomly divided into a barrier plot and a non-barrier plot. Barrier plots were subjected to a root pruning treatment in March of 2001 in which a trenching machine was used to dig a 0.2 m wide x 0.9 m deep trench along both sides of the plot at a distance of 1.5 m from the trees to separate root systems of pecan and cotton. A double layer of 0.15 mm-thick polyethylene sheeting was used to line the ditch prior to mechanical backfilling. The barrier plots thus served as the tree root exclusion treatment, preventing interaction of

tree and cotton roots, while the non-barrier plots, which did not receive this treatment, served as the tree-crop competition treatment.

Microplots and Fertilizer Application

For this study, cotton (DP 458 B/RR) was planted in rows 0.91 m apart at 16 rows per alley in a north-south orientation on 16 May 2001, after disking of the alleys. Conventional insecticide and herbicide were applied during the growing season as recommended. In each plot, one microplot (2.60 m x 0.76 m), containing 8-10 plants, was established on the first, fourth and eighth rows of cotton, respectively (going west to east in each plot) (Figure 4-1). To quantify nutrient competition, ^{15}N enriched fertilizer ($(\text{NH}_4)_2\text{SO}_4$, 5% atom enrichment) was uniformly hand-applied to microplots at a rate of $89.6 \text{ kg N ha}^{-1}$ on 19 June 2001 at the same time, rate and formulation as the regular fertilizer application (Timmons and Cruse 1990). Each microplot was arranged so that one of the pecan trees in the tree row was in the center and could serve as the target tree for ^{15}N sampling.

Sampling Methods

Six cotton plants (aboveground portions) from each microplot were sampled for ^{15}N content in leaf, stem and boll components. Cotton leaf samples were collected on 8 November 2001 prior to leaf senescence. The same plants were later harvested at physiological maturity on 4 December 2001, and separated into stem and boll components. In addition, foliar samples from each associated pecan tree were collected on 10 October 2001. For this purpose, the tree canopy was divided into an upper and lower half, and leaves were collected via shotgun harvest method from all four cardinal directions in both the halves to provide one composite leaf sample per tree.

Following collection, all plant tissue samples were dried at 65°C for 72 hours. In preparation for combustion analysis, all green plant tissue samples (cotton leaves and stems, and tree leaves) were ground with a model 4 Wiley Mill (Arthur H. Thomas Company, Philadelphia, Pennsylvania) to pass through a 1 mm screen, and then re-ground using a burr coffee grinder. Both grinders were thoroughly cleaned between samples to prevent cross-contamination of the ^{15}N plant material. Cotton lint was de-seeded and manually shredded with scissors in preparation for analysis.

Soil cores, measuring 120 cm in length and 3.5 cm in diameter, were collected in pairs at random points within each microplot in January 2002, using a tractor-mounted hydraulic corer and polyethylene collection tubes. The cores were divided into 15 cm increments to a depth of 120 cm, composited for each microplot depth, air dried, and a subsample was fine-ground with a mortar and pestle.

For determination of total N and ^{15}N concentrations, subsamples of the ground plant material and soil samples were analyzed by the University of Florida Geological Sciences Department (Gainesville, Florida) using a Finnigan-MAT DELTA^{plus} isotope ratio mass spectrometer with a ConFlo III interface attached to a Costech ECS 4010 elemental analyzer (Scheepers et al. 1989). Percent nitrogen derived from fertilizer, percent utilization of fertilizer nitrogen, and percent nitrogen recovery in soil, were calculated from the enrichment data to determine the degree of interspecific competition for nitrogen.

Percentage of plant nitrogen derived from fertilizer (NDF), a measure of the relative amounts of N a crop obtains from the soil and from applied fertilizer, was calculated as follows (Wienhold et al. 1995):

$$\text{NDF (\%)} = 100 * (a - b) / (c - d) \quad (4-1)$$

where

a = atom % ^{15}N abundance in cotton leaf, stem, seed cotton, or tree leaf;

b = atom % ^{15}N abundance in control cotton leaf, stem, seed cotton, or tree leaf;

c = atom % ^{15}N abundance of fertilizer; and

d = natural atom % ^{15}N abundance.

Percentage utilization of fertilizer N (UFN), a measure of fertilizer use efficiency, was calculated for cotton plants and pecan foliage as follows (Wienhold et al. 1995, Barber et al. 1996):

$$\text{UFN (\%)} = (\% \text{NDF} * S) / R \quad (4-2)$$

where

%NDF = percentage of plant nitrogen derived from fertilizer;

S = kg N ha^{-1} in cotton leaf, stem, seed cotton, or tree leaf; and

R = kg N ha^{-1} applied.

Percentage recovery of ^{15}N fertilizer in soil (RFN_{soil}), a measure of the applied ^{15}N remaining in soil, was determined using the following equation (De Mattos 2000):

$$\text{RFN}_{\text{soil}} (\%) = 100 * ((a - c) / (b - c)) * (N_p / N_f) \quad (4-3)$$

where

a = atom % ^{15}N abundance in fertilized soil material;

b = atom % ^{15}N abundance in labeled N fertilizer;

c = atom % ^{15}N abundance in non-fertilized soil (average background level);

N_p = total N of soil sample (in g); and

N_f = total amount of ^{15}N applied to the soil as labeled fertilizer (g).

Data Analyses

Statistical analyses were performed using SAS 8.2 for Windows (SAS Institute, Cary, North Carolina) using the Proc Mixed procedure within the framework of a split block design. The Shapiro-Wilk's test, in combination with ocular inspection of frequency distributions, was used to test all data for normal distribution. Logarithmic [$\log(x + 1)$] or arcsin transformation was conducted on data when such transformation improved normality. Differences between means were determined using the Least Squares Means procedure. Treatment effects were considered significant at $\alpha = 0.05$.

Results

Aboveground Biomass

The barrier treatment resulted in a 58.4% increase in total aboveground biomass of cotton plants compared to the non-barrier treatment (5750.26 kg ha⁻¹ vs. 3629.09 kg ha⁻¹, respectively) (Table 4-1). Total biomass also varied significantly by row ($p=0.0257$) in the non-barrier treatment. Cotton foliage biomass varied significantly by treatment ($p=0.0474$), with leaf biomass in the barrier treatment being 38.3% higher than that in the non-barrier treatment (1126.48 kg ha⁻¹ vs. 814.69 kg ha⁻¹, respectively). Within the barrier treatment, no significant difference among rows was observed for leaf biomass; however, leaf biomass increased significantly at Row 8 ($p=0.0180$) in the non-barrier treatment, representing a 66.1% increase over Row 1.

For cotton stem, biomass varied by treatment ($p=0.0135$) and by row ($p=0.0109$) (Table 4-1). Stem biomass was 66.4% higher in the barrier than the non-barrier treatment (3815.28 kg ha⁻¹ vs. 2293.19 kg ha⁻¹, respectively). Within each treatment, stem biomass

increased significantly with increasing distance from the tree, occurring at Row 4 in barrier ($p=0.0304$) and Row 8 in non-barrier ($p=0.0112$) treatments.

Seed cotton biomass was significantly different between treatments ($p=0.0493$) and rows ($p=0.0020$) (Table 4-1). Overall, seed cotton biomass in barrier treatment was 55.1% greater than that in non-barrier treatment ($808.51 \text{ kg ha}^{-1}$ vs. $521.21 \text{ kg ha}^{-1}$, respectively). For the barrier treatment, Row 1 had significantly higher seed cotton biomass than Rows 4 and 8. Seed cotton biomass in the non-barrier treatment showed no significant variation among rows.

Average dry leaf biomass of pecan trees was similar for both treatments, with $2516.40 \text{ kg ha}^{-1}$ for barrier treatment and $2580.60 \text{ kg ha}^{-1}$ for non-barrier treatment, respectively, based on litter trap collection data obtained from a separate study at the site (Zamora and Jose, unpublished data).

Nitrogen Concentration and Content

For each type of plant tissue analyzed, nitrogen concentrations were not affected by treatment or row, except for cotton leaf, which had a higher N concentration in Rows 4 and 8 in barrier treatment (Table 4-2). Nitrogen content, however, was affected by both treatment and row. In particular, the barrier treatment resulted in a 66.8% increase in total aboveground nitrogen content in cotton (83.02 kg ha^{-1}) compared to the non-barrier (49.77 kg ha^{-1}) treatment.

Nitrogen concentration of cotton foliage in the barrier treatment was 14.1% higher than in the non-barrier treatment, although not a statistically significant increase (Table 4-2). However, leaf nitrogen content was 56% higher in the barrier treatment ($p=0.0409$) than the non-barrier treatment (%N=42.04 and 26.95, respectively). Within the non-

barrier treatment, average leaf nitrogen content was significantly higher for Row 8 (%N=33.37) compared to Row 1 (%N=20.97).

Stem nitrogen concentrations averaged 0.99% as a whole, and did not differ across rows (Table 4-2). However, stem nitrogen content was 80.7% greater in the barrier treatment ($p=0.0073$), and showed a significant increase in Rows 4 and 8 of the barrier treatment.

Seed cotton nitrogen concentration showed no significant difference across rows, averaging 0.24% and 0.23% N for barrier and non-barrier treatments, respectively (Table 4-2). Seed cotton nitrogen content, although not significant between treatments, was significantly higher in Row 1 than in Row 4 of the barrier treatment.

For pecan foliage, percent nitrogen concentration was 2.16% in barrier and 2.27% in non-barrier treatments, respectively, which did not represent a significant difference (Table 4-4). Nitrogen concentration of senesced leaves was 1.88%, based on samples obtained from a separate control area. Canopy nitrogen content was also similar for both treatments, with 54.36 kg ha⁻¹ for barrier and 58.58 kg ha⁻¹ for non-barrier treatments, respectively. Leaf litter nitrogen content was estimated to be 47.31 kg ha⁻¹ for barrier and 48.52 kg ha⁻¹ for non-barrier treatments, representing the potential nitrogen deposition from leaf litter.

Uptake of Fertilizer Nitrogen

The nitrogen derived from fertilizer (NDF) in cotton leaf, stem and seed cotton showed significant differences between treatments (Table 4-3). Overall, NDF in cotton leaf was significantly ($p=0.0019$) lower in the barrier treatment (15.82%) compared to the non-barrier treatment (20.40%), representing a 22.5% decrease. However, NDF

increased with increasing distance from trees in the non-barrier treatment, becoming significantly higher for Row 8 ($p=0.0073$).

A similar trend was observed for cotton stem, with significantly ($p=0.0048$) lower NDF for stems in the barrier treatment (17.30%) compared to those in the non-barrier treatment (21.15%) (Table 4-3). The NDF for cotton stem also increased across rows in the non-barrier treatment, becoming significantly higher at Row 8 ($p=0.0038$). The NDF for seed cotton, which did not vary significantly according to row or treatment, was 14.76% and 16.95%, respectively, for the barrier and non-barrier treatments. The NDF for pecan foliage did not vary significantly between treatments, averaging -0.026% for barrier treatment and 0.063% for non-barrier treatment, respectively (Table 4-4). In this instance, a negative value for NDF and UFN in the barrier treatment was possible because the observed ^{15}N abundance was minutely lower than the background average.

Fertilizer Nitrogen Use Efficiency

Total fertilizer N use efficiency for leaf, stem and seed cotton combined was 15.13% for barrier plants and 11.70% for non-barrier plants, respectively, representing an overall increase in total UFN of 29.3% ($p=0.0340$) (Table 4-3). Total UFN increased from outer to inner rows and was significant for Row 8 in both barrier ($p=0.0147$) and non-barrier ($p=0.0006$) treatments. Overall, utilization of fertilizer nitrogen was similar in both cotton leaf and stem, and higher than UFN in seed cotton, for both treatments.

For cotton foliage, UFN was similar for both barrier (7.37%) and non-barrier (6.25%) treatments (Table 4-3). However, UFN of cotton leaf increased with increasing distance from tree base, becoming significantly higher at Row 8 ($p=0.0051$) in the non-barrier treatment. A significantly higher UFN for stem was observed for barrier (7.46%)

plants compared to non-barrier (5.22%) plants. In addition, UFN for stem varied by treatment and row, being significantly higher at Row 8 for both barrier ($p=0.0122$) and non-barrier ($p=0.0069$) treatments. The UFN of seed cotton was significantly higher in the barrier (0.29%) than the non-barrier (0.23%) treatment ($p=0.0348$), with no significant row effects. The UFN of pecan foliage was not significantly different between treatments, averaging -0.025% for barrier treatment and 0.037% for non-barrier treatment, respectively (Table 4-4).

Atom Percent ^{15}N Abundance and Nitrogen Concentration in Soil

Overall, atom % ^{15}N abundance in soil was found to be similar ($p=0.4869$) in barrier and non-barrier treatments based on isotopic analysis of the 15 cm soil core increments (Figure 4-2). Rows were also not significant ($p=0.6402$). However, depth was determined to be significant ($p<0.0001$), and there was an interaction between treatment and depth ($p=0.0308$). In the non-barrier treatment, the % ^{15}N distribution was uniform across rows and depths. However, in barrier treatment, % ^{15}N increased with depth, with values for upper layers (0-60 cm) being similar to those in the non-barrier treatment, and those for lower layers (60-105 cm) being higher.

Nitrogen concentration in soil did not vary significantly by treatment ($p=0.8820$) or by row ($p=0.2404$) (Figure 4-2). However, N concentration decreased significantly with depth ($p<0.0001$) at 15-30 cm depth and below.

Recovery of ^{15}N in Soil

A comparison of 30 cm soil increments (0-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm depths) showed that percent recovery of ^{15}N at the end of the growing season did not differ between treatments ($p=0.3251$) (Table 4-5). However, depth was significant

($p < 0.0001$), and the interaction between treatment and depth was significant ($p = 0.0039$). Specifically, the treatment \times depth interaction at the 90-120 cm depth showed a decrease ($p = 0.0207$) in ^{15}N recovery in the non-barrier treatment, where the rate of recovery was 2.08% compared to 3.93% in the barrier treatment. Total % ^{15}N remaining in soil at the end of the growing season for all depths combined was 18.94% for barrier treatment and 14.55% for non-barrier treatment, respectively.

Discussion

Overall, we observed that cotton plants in the barrier treatment had a 58.45% higher total aboveground biomass compared to the non-barrier treatment. Cotton foliage biomass, for example, was 38.30% higher in the barrier than the non-barrier treatment. Stem and seed cotton biomass were also significantly higher in the barrier treatment.

Similar results have been observed for other studies employing belowground root barriers in alley cropping systems. Miller and Pallardy (2001) studied belowground competition in a maize-silver maple (*Acer saccharinum* L.) alley cropping system in north-central Missouri. In their study, which was located on a Mexico series soil (a fine, montmorillonitic, mesic, Udollic Ochraqualf), they observed a 27.77% higher maize grain yield in plots with root barriers compared to plots without them. Similarly, Jose et al. (2000b) observed a 67.33% higher grain yield and a 37.21% higher stover biomass in root barrier plots, in their study of a black walnut (*Juglans nigra* L.)-maize alley cropping system on a Parke Silt Loam soil (Ultic Hapludalf) soil in Indiana. Singh et al. (1989) observed that root barriers in a sorghum (*Sorghum bicolor* Moench)-leucaena (*Leucaena leucocephala* Lam. de Wit) alley cropping system in semiarid India, raised sorghum grain yields from 0.42 Mg ha^{-1} to 1.63 Mg ha^{-1} . However, in each of these

studies, competition for water was identified as the primary factor causing biomass reductions, rather than competition for nutrients, since water deficits resulted in smaller crop size and reduced fertilizer use efficiency. Findings by Wanvestraut et al. (2003), who conducted a companion study to the one reported here, confirmed the occurrence of water competition in the current study site. Cotton lint yield in their study was reduced by 21% due to belowground competition for water in the absence of a root barrier.

For pecan trees, average tree diameter and dry leaf biomass did not differ between treatments. However, a reduction in tree growth and yield would be expected in response to the root pruning treatment. Miller and Pallardy (2001), for example, observed a 20% reduction in annual radial growth of silver maple at the end of the first growing season after root barrier installation. These parameters were not assessed in our study.

Although nitrogen concentrations in cotton tissues were not affected by treatment, nitrogen content was affected by both treatment and row. Cotton plants in the barrier treatment had a 56% higher nitrogen content than those in the non-barrier treatment because of the greater plant biomass in the barrier treatment. For both treatments, total nitrogen content increased with increasing distance from the tree, with Row 8 being significantly higher than Row 1 for both treatments. This row effect is not fully understood, but differences in nitrogen content may have resulted from more favorable soil moisture or light conditions in the mid-alley rows.

The root barrier had no significant effect on pecan leaf nitrogen concentration or canopy nitrogen content. These findings are in contrast to the results of Jose et al. (2000b), who observed leaf nitrogen concentration in 15-year-old black walnut to be 15.5% lower in barrier trees than non-barrier trees. In that study, the non-barrier tree

roots apparently acquired N from the fertilized alley, producing a higher nitrogen concentration in the black walnut leaves. The reasons for the differing results are not clear, although they could be attributed to tree age and root system development. The roots of older trees (as in our study) would be expected to have access to a wider and deeper pool of soil nutrients compared to younger trees, and would therefore be less dependent on near-surface fluctuations in soil nitrogen availability.

Nitrogen uptake in crops can be supplemented via the mineralization of tree leaf and root litterfall, which is dictated largely by the litter quality, which differs among tree species and management (Handayanto et al. 1997). Pecan trees in our study were estimated to have an average of 56.47 kg ha⁻¹ in total canopy nitrogen content, which, allowing for resorption, results in an estimated 47.91 kg ha⁻¹ of nitrogen being deposited to the orchard floor as leaf litter on a yearly basis (Table 4-4). This build-up and decomposition of litterfall, combined with rootfall and deposition of other organic debris, may serve to augment soil N supplies and thus reduce the amount of nitrogen fertilizer required for cotton production (Sanginga et al. 1990, Seiter and Horwath 1999).

Rhoades et al. (1998), for example, in their study of a sorghum-mimosa (*Albizia julibrissin*) alley cropping system on a highly-weathered Ultisol (Typic Hapludult) in Georgia, found that tree-mulch additions enhanced crop biomass production and N uptake by 2 to 3.5 times in both high and low moisture conditions. In another study, Seiter and Horwath (1999) demonstrated that soil organic matter could increase by 4 to 7% in alley cropping systems with alder (*Alnus sinuata*) and maize in comparison to maize monocultures following four years of cropping on a Chehalis soil series (a fine silty, mesic, Ultic Haploxeroll) in Oregon.

Overall, our 12-25% NDF range in cotton plants was lower than the 33-40% NDF reported for cotton in other studies (Rochester et al. 1994, Gibb et al. 2002). Our non-NDF range of 75-88% was higher than the 67-68% rate reported in other studies (Rochester et al. 1993, Gibb et al. 2002). Thus, use of indigenous soil N in our study appears to have been generally higher than average. This is perhaps due to an abundance of soil nitrogen mineralized from the long-term deposition of pecan leaf and root litter in the orchard.

With regard to the specific effects of treatment on NDF, NDF in cotton leaf and stem was significantly lower in the barrier treatment compared to the non-barrier treatment, representing a decrease of 22.5% and 18.20%, respectively. Apparently, cotton plants in the barrier treatment took up more of their nitrogen from the nitrogen already present in the soil than the applied fertilizer nitrogen. One of the factors that could influence nitrogen allocation patterns in intercropped cotton is the synchrony of crop and tree nutrient demand (Xu et al. 1993, Handayanto et al. 1997, Rowe et al. 1999). While initial nutrient demand in cotton is low prior to fruiting or flowering (Ayala and Doerge 2001, Crozier 2003), demand intensifies about 45 days after emergence, with a prolonged peak about two weeks after first bloom, when flower production, boll filling, and boll maturation are most active (Crozier 2003). In contrast, pecan trees in our study exhibited a pattern of early leaf development, indicating heavy nutrient demand early in the year. Thus, tree-root acquisition of soil N may have occurred well before cotton stand establishment, leaving soil in the non-barrier treatment less rich in N than in the barrier treatment. This may explain the higher dependency on fertilizer N exhibited in non-barrier plants compared to barrier plants.

The NDF level in pecan leaves was minimal but existent (0.063%) for non-barrier trees, and minimally negative for barrier trees. Pecan has been shown to recover as much as 19.5% of applied fertilizer, if applied early in the growing season (Kraimer et al. 2001). However, as explained earlier, the bulk of nitrogen taken up by the pecan trees in our study was obtained prior to the June application of fertilizer. It may be possible that there is substantial NDF stored elsewhere in the tree, such as in roots, stems or branches; however, these components were not measured in our study.

Total UFN for leaf, stem and seed cotton combined was 15.13% for barrier plants and 11.70% for non-barrier plants, respectively, representing an overall decrease in total UFN of 22.67%. Here, plants in the non-barrier treatment showed reduced growth, and so were unable to utilize the available fertilizer efficiently, a result observed for maize plants in previous research (Wienhold et al. 1995, Jose et al. 2000b). Total UFN increased from outer to inner rows and was significant for Row 8 in both barrier and non-barrier treatments. Utilization of fertilizer nitrogen was similar in both cotton leaf and stem, and much higher than UFN in seed cotton, for both treatments. The UFN for pecan in non-barrier was 0.037%, indicating minimal uptake and utilization of the fertilizer N.

When evaluating soil N status at the end of the growing season, we observed that soil N concentration followed a predictable pattern of decline at 15 cm depth and below in both treatments. This trend would be expected given the shallow root zone of cotton and the susceptibility of N to leaching in the sandy soil of the study site.

We also observed that atom %¹⁵N concentration remained uniform for the non-barrier treatment, while that for the barrier treatment increased at 60 cm depth and below. A similar treatment x depth interaction was observed for %¹⁵N recovery, where tree root

uptake at the 90-120 cm depth apparently reduced the rate of recovery to 2.08% in the non-barrier treatment compared to 3.93% in the barrier treatment. Overall, for all depths combined, %¹⁵N recovery in soil was 18.94% for barrier and 14.55% for non-barrier treatments, respectively, somewhat lower than the 20-25% recovery range reported by other researchers (Karlen et al. 1996, Gibb et al. 2002).

Various factors in our study may have affected recovery of fertilizer-¹⁵N in the soil. Tree roots may have accessed a portion of the fertilizer nitrogen in the non-barrier treatment, thus reducing recovery in the soil. In addition, a substantial amount of N may have been lost to biogeochemical mechanisms. For example, Kraimer et al. (2001) reported that ¹⁵N levels in soil under pecans were highest at soil depths just above the water table (280 cm), indicating losses due to leaching in the five months after application. In another study, Karlen et al. (1996) speculated that 50% of ¹⁵N applied to their study was lost via volatilization, denitrification or leaching below the crop root zone. Likewise, Rochester et al. (1993) noted an exponential decline of ¹⁵N recovery with time, which they attributed to biological immobilization and possibly denitrification. Because the ¹⁵N-labeled fertilizer in our study was necessarily applied as a side-dress in a single application, a significant portion may have leached out of the system, given the high rainfall observed in July (139.19 mm) and August (217.42 mm) of 2001, the two months following application.

Overall, these findings illustrate the importance of proper nutrient management in alley cropping systems in order to achieve most efficient use of nitrogen inputs. As with any cotton production system, appropriate fertilizer management should be followed, in order to improve fertilizer-N efficiency, supply crop needs for nitrogen, and reduce losses

of nitrate ($\text{NO}_3\text{-N}$) due to leaching (Ayala and Doerge 2001). This includes use of soil tests, monitoring of petiole nitrate levels, and split applications of fertilizer by use of side-dress and/or fertigation applications. The use of commercial nitrification inhibitors is also suggested as a means to increase fertilizer nitrogen recovery and lint yield, as a delay in nitrification has been shown to improve total nitrogen uptake in cotton, especially during the boll maturation period (Freney et al. 1993, Rochester et al. 1994). In addition, conservation tillage (e.g., no-tillage or strip-till) and winter cover management practices may be applied, to maximize accumulation of plant surface mulch and thus conserve water and increase soil fertility (Varco et al. 1999). Taken together, these measures can help to achieve more efficient synchrony of the nutrient, water and light demand functions of cotton and pecan during the growing season.

Conclusions

Although nitrogen is shared between cotton and pecan according to the competitive abilities of the two species, existing soil nutrient levels, water availability, and temporal plant nutrient demands are critical factors in this process. Our results indicate that cotton plants are subject to competition for nitrogen; companion studies have indicated that they are subject to competition for water also. Competition for nitrogen was alleviated to a great extent by the application of fertilizer nitrogen, and possibly by existing soil nitrogen reserves from the deposition of pecan litterfall. Further, nitrogen uptake and allocation patterns in both pecan and cotton were influenced largely by temporal differences in N demand and apparently by the abundance of mineralized nitrogen in soil. We observed increases in nitrogen content of cotton in the presence of root barrier, although the barrier had no significant effect on pecan leaf nitrogen

concentration or canopy nitrogen content. The NDF was lower for cotton in barrier plants, indicating that cotton in this treatment was taking up a higher percentage of its nitrogen from nitrogen already present in the soil. The NDF in pecan was minimal, indicating an early and substantial uptake of N prior to the cotton season and fertilizer application. However, it may be possible that there is substantial NDF stored elsewhere in the tree, such as in roots, stems or branches. Total UFN was higher in barrier cotton plants, indicating a greater ability to utilize the available fertilizer efficiently. In soil, depth was the primary factor influencing fertilizer N concentrations and recovery rates. However, a treatment x depth interaction was observed at the lowest depth in the non-barrier treatment, where the ^{15}N recovery rate was lower than that in the barrier treatment. Apparently, fertilizer nitrogen in the non-barrier treatment was taken up by tree roots from this deeper horizon. Overall, the alley cropping system in this study exhibits potential for nutrient capture and increased fertilizer use efficiency, given the apparent ability of pecan trees to intercept nitrogen fertilizer at lower depths and to provide litterfall to the cropping zone.

Table 4-1. Biomass of cotton leaf, stem and seed cotton in barrier and non-barrier treatments.

Treatment	Row	Biomass (kg ha ⁻¹)			
		Leaf	Stem	Seed cotton	Total
Barrier	1	1166.71 a ¹ (102.32) ²	2946.95 a (530.21)	1147.25 a (174.08)	5260.91 a
	4	1066.13 a (105.97)	4073.43 b (513.59)	625.76 b (59.69)	5765.32 a
	8	1146.59 a (136.25)	4425.45 b (468.53)	652.51 b (34.47)	6224.55 a
	Mean ³	1126.48 (114.85)	3815.28 (504.11)	808.51 (89.41)	5750.26
No barrier	1	623.59 a (123.80)	1689.72 a (227.47)	528.42 a (37.94)	2841.73 a
	4	784.51 ab (113.12)	2092.03 a (195.81)	486.24 a (49.71)	3362.78 a
	8	1035.96 b (58.65)	3097.82 b (370.44)	548.97 a (11.27)	4682.75 b
	Mean ³	814.69 (98.52)	2293.19 (264.57)	521.21 (32.97)	3629.09
p value ⁴		0.0474	0.0135	0.0493	0.0076

¹ Within-treatment values followed by the same lowercase letter are not significantly different at the 0.05 level of probability.

² Standard errors of the mean are given in parentheses.

³ Mean indicates the treatment mean.

⁴ p value indicates the significance between treatment means.

Table 4-2. Nitrogen concentration and nitrogen content in cotton leaf, stem and seed cotton in barrier and non-barrier treatments.

Treatment	Row	Nitrogen concentration (%)			Nitrogen content (kg ha ⁻¹)			
		Leaf	Stem	Seed cotton	Leaf	Stem	Seed cotton	Total
Barrier	1	3.45 a ¹ (0.12) ²	0.95 a (0.06)	0.21 a (0.02)	40.19 a (3.72)	28.0 a (5.12)	2.40 a (0.44)	70.59 a
	4	3.90 b (0.06)	1.04 a (0.07)	0.25 a (0.02)	41.78 a (4.54)	42.95 b (7.07)	1.60 b (0.25)	86.33 ab
	8	3.83 b (0.12)	1.07 a (0.07)	0.26 a (0.04)	44.16 a (5.63)	46.20 b (3.35)	1.77 ab (0.36)	92.13 b
	Mean ³	3.73 (0.10)	1.02 (0.07)	0.24 (0.03)	42.04 (4.63)	39.05 (5.18)	1.92 (0.35)	83.02
No barrier	1	3.26 a (0.20)	0.97 a (0.10)	0.23 a (0.02)	20.97 a (4.80)	17.13 a (3.94)	1.22 a (0.06)	39.32 a
	4	3.33 a (0.22)	0.90 a (0.05)	0.22 a (0.03)	26.52 ab (4.61)	18.99 a (2.49)	1.06 a (0.10)	46.57 ab
	8	3.21 a (0.09)	0.95 a (0.07)	0.25 a (0.04)	33.37 b (2.25)	28.71 a (2.18)	1.34 a (0.20)	63.42 b
	Mean ³	3.27 (0.17)	0.94 (0.07)	0.23 (0.03)	26.95 (3.89)	21.61 (2.87)	1.21 (0.12)	49.77
p value ⁴		0.0942	0.3540	0.6811	0.0409	0.0073	0.0554	0.0122

¹ Within-treatment values followed by the same lowercase letter are not significantly different at the 0.05 level of probability.

² Standard errors of the mean are given in parentheses.

³ Mean indicates the treatment mean.

⁴ p value indicates the significance between treatment means.

Table 4-3. Percentage of nitrogen derived from fertilizer (NDF) and percentage utilization of fertilizer nitrogen (UFN) for cotton leaf, stem and seed cotton in barrier and non-barrier treatments.

Treatment	Row	NDF (%)			UFN (%)			
		Leaf	Stem	Seed cotton	Leaf	Stem	Seed cotton	Total
Barrier	1	15.37 a ¹ (0.79) ²	17.60 a (1.24)	12.75 a (2.18)	6.86 a (0.66)	5.41 a (0.88)	0.31 a (0.05)	12.58 a
	4	15.31 a (1.40)	16.43 a (0.95)	18.23 a (4.11)	7.08 a (0.87)	7.74 ab (1.12)	0.31 a (0.06)	15.13 ab
	8	16.77 a (1.91)	17.88 a (2.00)	13.31 a (1.61)	8.17 a (1.22)	9.24 b (1.17)	0.26 a (0.06)	17.67 b
	Mean ³	15.82 (1.37)	17.30 (1.40)	14.76 (2.63)	7.37 (0.92)	7.46 (1.06)	0.29 (0.06)	15.13
No barrier	1	18.26 a (0.76)	18.98 a (0.66)	16.19 a (2.92)	4.37 a (1.12)	3.66 a (0.87)	0.22 a (0.04)	8.25 a
	4	19.32 a (0.76)	19.44 a (1.15)	13.96 a (1.27)	5.60 a (0.85)	4.05 a (0.42)	0.16 a (0.02)	9.81 a
	8	23.61 b (1.04)	25.04 b (1.18)	20.69 a (1.37)	8.79 b (0.69)	7.94 b (0.45)	0.31 a (0.05)	17.04 b
	Mean ³	20.40 (0.85)	21.15 (1.00)	16.95 (1.85)	6.25 (0.89)	5.22 (0.58)	0.23 (0.04)	11.70
p value ⁴		0.0019	0.0048	0.1333	0.2580	0.0161	0.0348	0.0340

¹ Within-treatment values followed by the same lowercase letter are not significantly different at the 0.05 level of probability.

² Standard errors of the mean are given in parentheses.

³ Mean indicates the treatment mean.

⁴ p value indicates the significance between treatment means.

Table 4-4. Percentage of nitrogen derived from fertilizer (NDF), percentage utilization of fertilizer nitrogen (UFN), and other physiological parameters for pecan trees in barrier and non-barrier treatments.

Parameter	Treatment		p value ¹
	Barrier	No barrier	
Average tree dbh (cm)	216.62 (9.47) ²	221.35 (5.99)	0.6837
Average dry leaf biomass (kg tree ⁻¹)	83.88 (10.18)	86.02 (8.36)	0.8749
Leaf nitrogen concentration (fresh) (%)	2.16 (0.05)	2.27 (0.07)	0.3846
Leaf ¹⁵ N concentration (fresh) (%)	0.366 (0.002)	0.370 (0.001)	0.2754
Canopy nitrogen content (kg tree ⁻¹)	1.81 (0.22)	1.95 (0.19)	0.6513
Canopy nitrogen content (kg ha ⁻¹)	54.36 (6.60)	58.58 (5.69)	0.6406
Leaf NDF (fresh) (%) ³	-0.026 (0.04)	0.063 (0.02)	0.0880
Leaf UFN (fresh) (%) ³	-0.025 (0.03)	0.037 (0.01)	0.0975
Leaf litter nitrogen concentration (%)	1.88 (0.03)	1.88 (0.03)	--
Leaf litter nitrogen content (kg tree ⁻¹)	1.58 (0.19)	1.62 (0.16)	--
Leaf litter nitrogen content (kg ha ⁻¹)	47.31 (5.74)	48.52 (4.71)	--

¹ p value indicates the significance between treatment means. Since senesced leaf litter samples were obtained from a control area, p values for these parameters are not shown.

² Standard errors of the mean are given in parentheses.

³ A negative value for NDF or UFN is possible when observed ¹⁵N abundance fluctuates below the background average.

Table 4-5. Percentage of ^{15}N recovery in soil at end of growing season in barrier and non-barrier treatments.

Treatment	Row	% ^{15}N recovery in soil				
		0-30 cm	30-60 cm	60-90 cm	90-120 cm	Total
Barrier	1	9.39 (1.81) ¹	1.24 (0.08)	4.13 (2.74)	4.78 (2.05)	19.55 (1.11)
	4	6.01 (1.62)	1.70 (0.42)	6.29 (3.73)	2.09 (0.54)	16.08 (1.07)
	8	10.87 (3.48)	1.70 (0.32)	3.70 (0.70)	4.92 (2.07)	21.18 (1.23)
	Mean ²	8.76 a ³ (1.42)	1.55 b (0.18)	4.71 c (1.48)	3.93 bc (0.98)	18.94 (0.65)
No barrier	1	6.26 (0.72)	1.67 (0.65)	2.39 (1.19)	1.48 (0.73)	11.80 (0.59)
	4	7.96 (0.90)	1.35 (0.18)	2.74 (0.93)	2.96 (2.55)	15.00 (0.87)
	8	10.70 (2.35)	2.30 (0.18)	2.05 (0.61)	1.79 (1.46)	16.84 (1.08)
	Mean ²	8.31 a (0.94)	1.77 b (0.24)	2.39 b (0.51)	2.08 c (0.95)	14.55 (0.50)
p value ⁴		0.8683	0.8418	0.2474	0.0207	0.3251

¹ Standard errors of the mean are given in parentheses.² Mean indicates the treatment mean.³ Means for a given treatment followed by the same lowercase letter are not significantly different at the 0.05 level of probability.⁴ p value indicates the significance between treatment means.

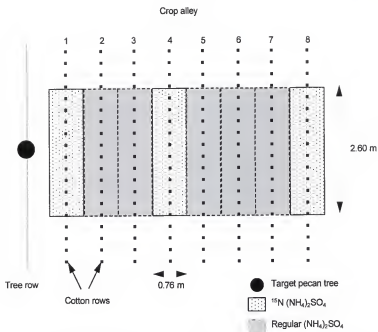


Figure 4-1. Plot layout showing location of ^{15}N -enriched microplots at the Jay, Florida agroforestry site.

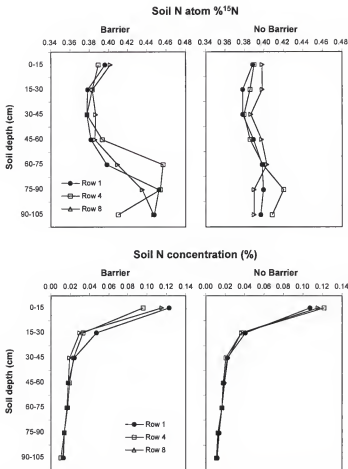


Figure 4-2. Mean atom %¹⁵N abundance and total %N in soil at end of growing season in barrier and non-barrier treatments.

CHAPTER 5 SUMMARY AND CONCLUSION

This study has examined nitrogen (N) dynamics in a pecan-cotton alley cropping system in the southern United States, specifically nitrogen mineralization patterns (Chapter 2), groundwater nitrate dynamics (Chapter 3), and tree-crop competitive effects (Chapter 4). Findings from these chapters are briefly summarized below.

In Chapter 2, we studied the effect of tree roots on nitrogen transformations in soil. We observed that temporal variations in net ammonification, nitrification and mineralization were driven primarily by environmental factors (e.g., soil moisture content and soil temperature), and by initial ammonium and nitrate levels. However, these and other factors appear to have exerted a combined influence on N transformations over the study period. Mineralization varied by treatment during the first growing season, when non-barrier exhibited a higher mineralization rate than barrier treatment. During the winter-season dormant period, however, mineralization in non-barrier treatment experienced a significant decrease. Nitrification and mineralization rates in season two were the same for both barrier and non-barrier treatments. Lint yield reductions were observed in non-barrier treatment during both years compared to barrier treatment, likely due to interspecific competition for water. However, for 2002, differences in yield were more pronounced than the previous year, and are indicative of a short-lived fallow effect, which appears to have enhanced 2001 crop yields but then diminished by the second crop year. Source of N (chemical fertilizer vs. chicken manure) was found to have a significant effect on cotton yield as well, with inorganic fertilizer resulting in moderately

higher yields in the barrier treatment compared to poultry litter. Overall, the interactive dynamics imposed by the alley cropping configuration created competitive interactions for resources such as water and nitrogen, resulting in a decreased ability for nitrogen uptake in the non-barrier compared to the barrier treatment. This, in turn, may have resulted in a higher build-up of soil N in the non-barrier treatment. Effects of the pre-trial fallow period appear to have diminished by the second growing season.

In Chapter 3 we examined the safety net hypothesis to determine whether tree roots were able to capture nitrate and ammonium that had leached below the root zone of cotton. In general, the competitive presence of trees in non-barrier treatment resulted in decreased soil nitrate concentrations and leaching rates at lower depths compared to barrier treatment. Further, tree water uptake, in addition to cotton water uptake in the non-barrier treatment, may have decreased water drainage in comparison to the barrier treatment, thereby influencing leaching rates. Overall, the presence of tree roots was observed to be an important factor influencing the fate of nitrogen in the system.

In Chapter 4, we examined the effect of tree-crop competition for nitrogen on crop biomass, fertilizer use efficiency, and N recovery in soil. Results of this portion of the study showed that, although nitrogen was shared according to the competitive abilities of pecan and cotton, existing soil nutrient levels, water availability, and temporal plant nutrient demands were also critical factors in this process. Our results indicated that cotton plants were subjected to competition for nitrogen and perhaps water. Competition for nitrogen was alleviated to a great extent by the application of fertilizer nitrogen. Further, nitrogen uptake and allocation patterns in both pecan and cotton were influenced largely by temporal differences in N demand and the abundance of

mineralized nitrogen in soil. We observed increases in nitrogen content of cotton in the presence of root barrier, although the barrier had no significant effect on pecan leaf nitrogen concentration or canopy nitrogen content. NDF was lower for cotton in barrier plants, indicating that cotton in this treatment was taking up a higher percentage of its nitrogen from nitrogen already present in the soil. However, NDF in pecan was minimal, indicating an early and substantial uptake of N prior to the cotton season and fertilizer application. Total UFN was higher in barrier cotton plants, indicating a greater ability to utilize the available fertilizer efficiently. In soil, depth was the primary factor influencing nitrogen recovery, although a significant trend was observed at lower depths in the non-barrier treatment, where N recovery levels were lower than levels in barrier treatment. Apparently, fertilizer nitrogen was taken up by tree roots from these deeper horizons. Overall, the alley cropping system in this study exhibits potential for nutrient capture and increased fertilizer use efficiency, given the apparent ability of pecan trees to intercept nitrogen fertilizer and to provide litterfall to the cropping zone.

These related studies indicate that alley cropping systems provide a unique opportunity to manage fertilizer inputs for enhanced nutrient use efficiency and groundwater contaminant mitigation, albeit site specific. The relative impact upon these parameters will vary depending on tree and crop species, system design and management practices. Likewise, nutrient cycling patterns will be affected by relative mixtures of leaves and roots in a particular site, and by water- and temperature-driven rates of mineralization. Interspecific interactions must also be considered in light of crop production goals. Hence, additional research is needed to parameterize these factors for various alley cropping systems.

Overall, the findings from this study provide a unique contribution to our understanding of nutrient competition and groundwater nitrogen dynamics in pecan-cotton alley cropping systems. While findings are not specifically relevant to other systems, they at least offer the scientific basis to make pecan-cotton alley cropping and similar agroforestry systems an environmentally appealing and ecologically viable option for landowners.

APPENDIX LEACHMN PARAMETER INPUT VALUES

Table A-1. LEACHMN parameter input values used for modeling field drainage at the Jay, Florida agroforestry site.

Parameter	Input value*
Profiled depth	B30, NB30: 300 mm; B90, NB90: 900 mm
Soil segment thickness unit	B30, NB30: 30 mm; B90, NB90: 100 mm
Initial water table depth	1500 mm
Lower boundary condition	Free drainage
Clay	9%
Silt	18%
Organic carbon (upper-lower segments)	B30, NB30: 2.2-1.1%; B90, NB90: 2.2-0.1%
Matric potential	-20 kPa
Root density (upper segment)	B30, B90: 0.30; NB30, NB90: 0.25
Particle density: clay	2.65 kg dm ⁻³
Particle density: silt and sand	2.65 kg dm ⁻³
Particle density: organic matter	1.10 kg dm ⁻³
Field capacity	-5.0 kPa
Bulk density (upper-lower segments)	B30, NB30: 1.23-1.30 kg dm ⁻³ B90 and NB90: 1.23-1.59 kg dm ⁻³
SCS curve number	55
Plant growth period (calendar months)	B30, B90: 5-11; NB30, NB90: 3-12
Wilting point (soil)	-1500 kPa
Minimum root water potential	-3000 kPa
Root resistance	1.05
Crop cover	B30, B90: 0.8; NB30, NB90: 0.9
Synthesis efficiency factor	0.5
Humification fraction	0.2
C:N ratio: biomass and humus	10.5
Denitrification half-saturation constant	10 mg L ⁻¹
Limiting NO ₃ -N/NH ₄ -N ratio	8
Amount of nitrogen applied	89.6 kg ha ⁻¹ (for two seasons)
Number of water applications	200

* Abbreviations for treatment variables are as follows: barrier treatment at 30 cm depth (B30), non-barrier treatment at 30 cm depth (NB30), barrier treatment at 90 cm depth (B90), and non-barrier treatment at 90 cm depth (NB90).

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BIOGRAPHICAL SKETCH

Sam Allen was born in Stillwater, Oklahoma, on 27 April 1967. He grew up in Starkville, Mississippi, and attended Mississippi State University (MSU) for his B.A. (communication) and M.S. (agricultural and extension education) degrees. His interest in the field of agroforestry stems in part from his time as a Rotary Ambassadorial Scholar to the Philippines, where he studied agroforestry at the University of the Philippines at Los Baños and examined the effectiveness of an agroforestry extension program in Mindanao, southern Philippines. While in that nation, he also served as a communications consultant for an international agricultural consulting firm. In addition, he has served as a field worker for the MSU entomology and weed science departments, a news writer for the Mississippi Cooperative Extension Service, and an intern for the Institute for Hunger Education and Resources Training, an agricultural training facility located in Lake Wales, Florida.

Mr. Allen has conducted his Ph.D. research at the University of Florida on tree-crop interactions and environmental benefits of alley cropping systems for the southern United States. He looks forward to his continued involvement in the agricultural development arena both in the United States and overseas. He is married to Carina (Teri) Luna Allen, of Calamba, Laguna, Philippines.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



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May 2003


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